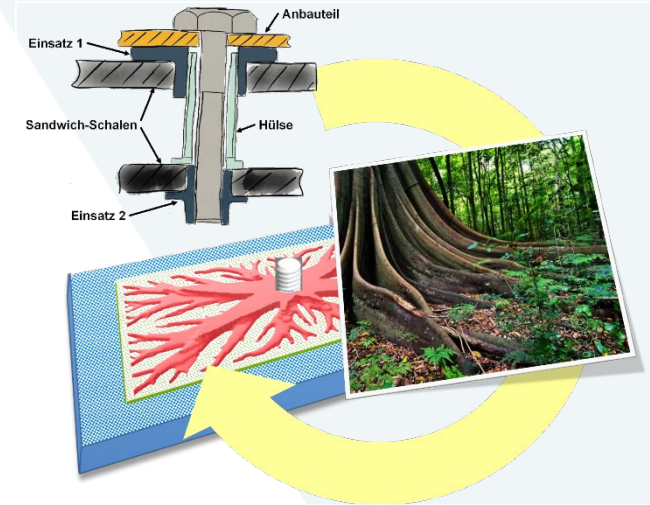


join!SLMti-cfk

Development of TiAl6V₄ inserts adapted to the compliance of CFK laminates for maximum fatigue strength



DI DDr. Jürgen M. Lackner

JOANNEUM RESEARCH Forschungsges.m.b.H., MATERIALS, Laser- & Plasma Processing

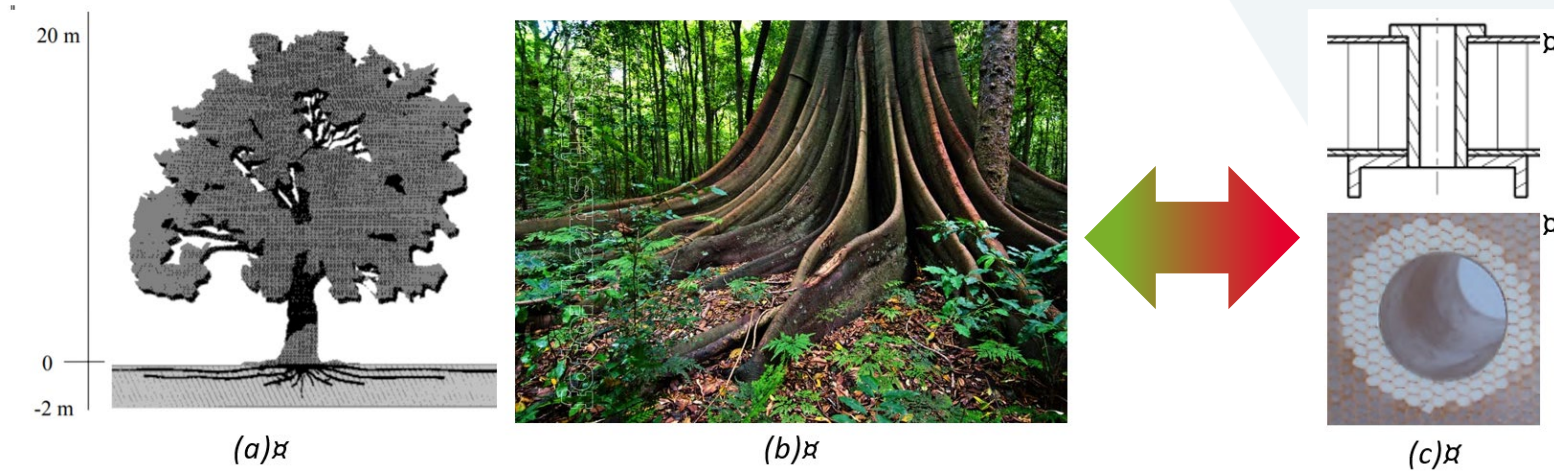
Niklasdorf - Vienna, 12.11.2025

Background of the project

- **Problem:** conventional solid metal inserts are far stiffer than thin CFK plies, producing highly localised stress peaks that initiate fibre breakage, matrix cracking and delamination under shear/out-of-plane loads.
- **Motivation:** a tuned, fine-featured metallic pad (bionic/lattice) matched to laminate compliance can redistribute loads, and increase load capacity and fatigue life.
- **Target applications:** aircraft interiors, UAV components and load-bearing hybrid details where weight, inspectability and regulatory compliance matter; project positions inserts for short-term uptake in interiors/UAVs and medium-term structural validation.

Background of the project

- Target: Biomimetic insert for joining CFRP components with attached parts

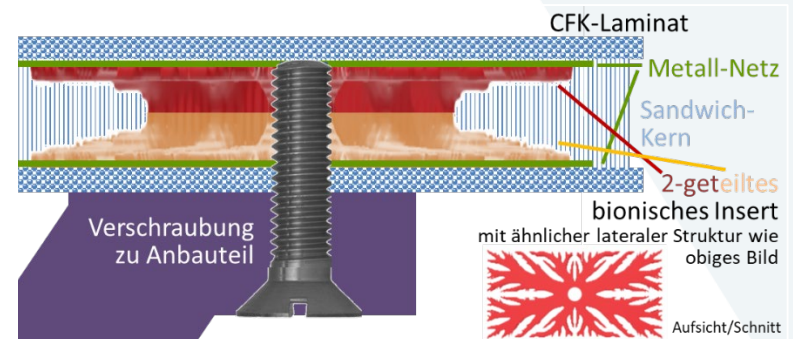
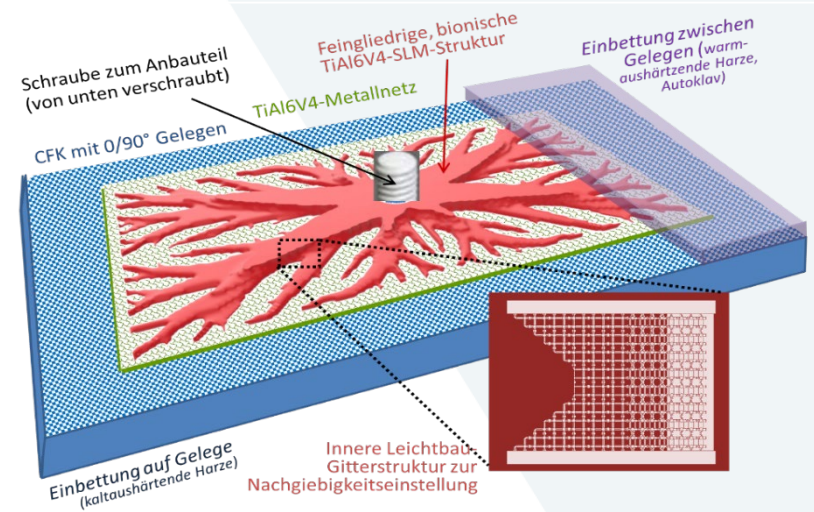


(a) Schematic representation of the root strands responsible for the mechanical stability of shallow-rooted trees and (b) structure of pronounced buttress roots above ground. (c) Comparison with the typical design of an insert with a resin-filled sandwich structure for increased strength.

Aim of the project

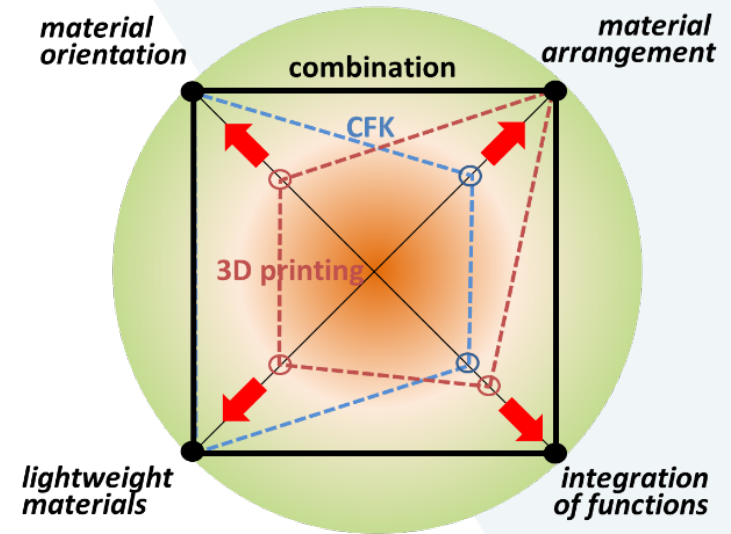
- Core objective:

Design and produce Ti-6Al-4V insert-pads manufactured by SLM on metal mesh whose effective compliance and load transfer behaviour are tuned to CFK laminates, thereby minimising local peak stresses and delamination risk.



Aim of the project

- **Scope:**
 - develop process chain (SLM → APPD coating → lamination),
 - digital element toolbox (topology/lattice designs),
 - demonstrators (monolithic & sandwich) and
 - SHM schemes to validate in-service inspectability.



Brief description of the consortium partners

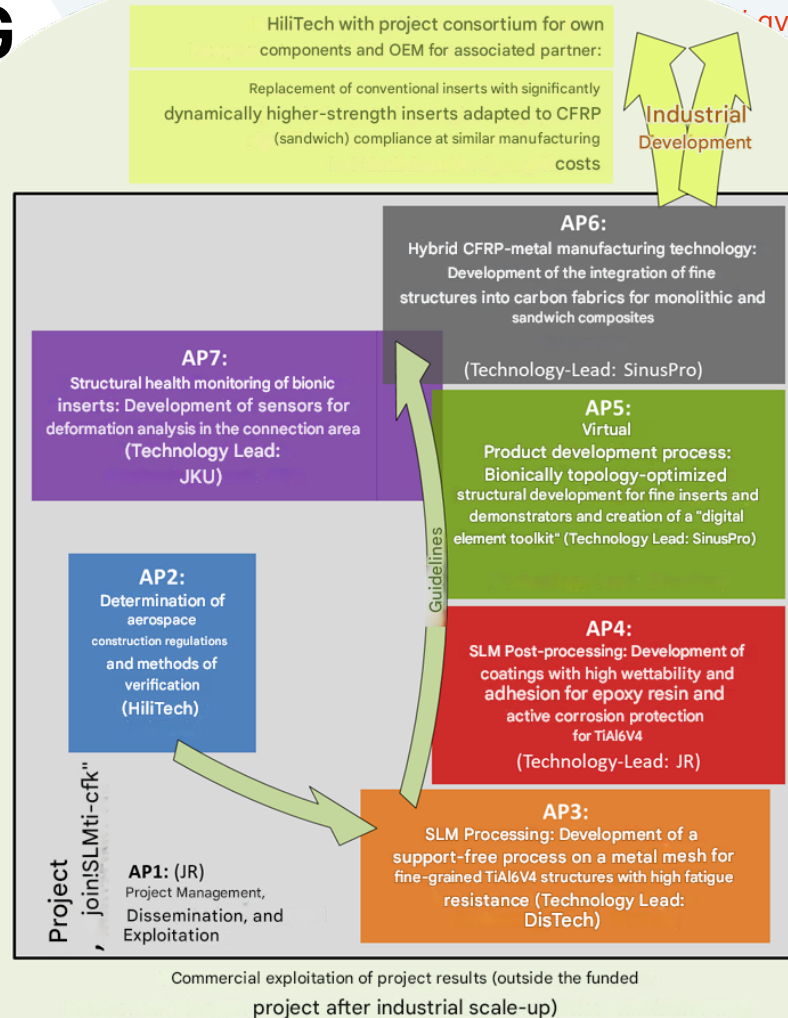
- **JOANNEUM RESEARCH:** SLM for fine Ti-6Al-4V, APPD coatings, metallography, process simulation — scientific lead.
- **DisTech:** industrial SLM adaptation, process up-scale and heat-treatment; manufacturing lead for support-free printing.
- **SinusPro:** virtual product development, topology & lattice optimisation (digital toolbox).
- **HiLiTECH:** CFK serial production, demonstrator selection and lamination/process integration.
- **JKU:** structural-health-monitoring (SHM) method development and lifetime models.
- **MCL:** high-resolution materials characterisation, fatigue & microstructural testing.



company liquidated in 2023 –
results, simulation models and all
project task transferred to
JOANNEUM RESEARCH

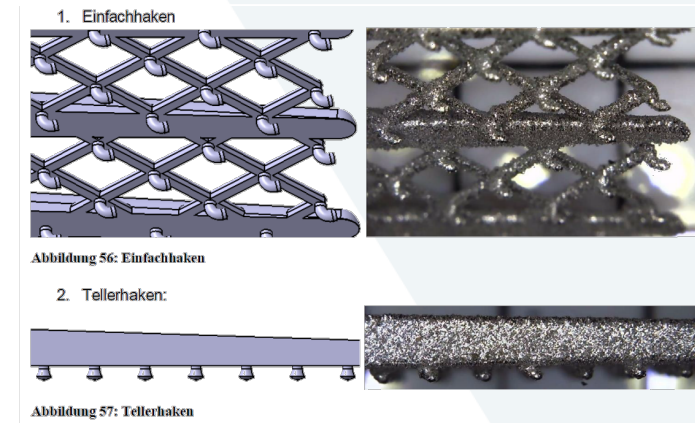


Work plan – Transdisciplinary Approach



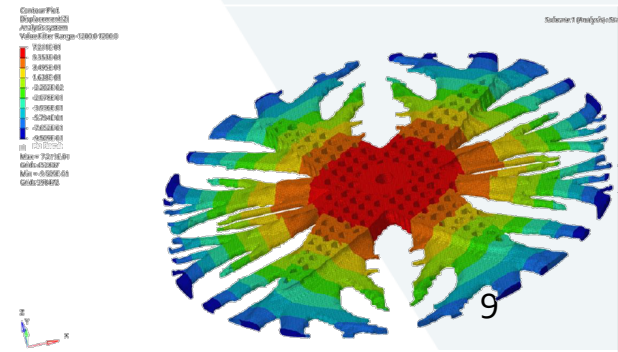
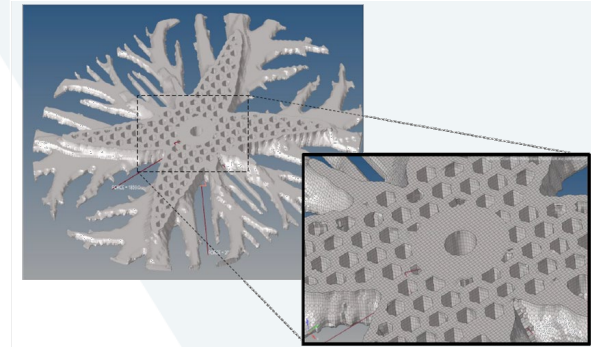
Project results - SLM process development for fine features

- **Achievement:** established support-free SLM processing strategies for printing fine lattice and hook geometries directly onto metal mesh pads; parameters chosen to minimise porosity and residual distortion on Ti-6Al-4V SLM surfaces.
- **Practical outcome:** repeatable production of printable lattice elements within process constraints (overhang, beam length) and a manufacturing route compatible with downstream coating and lamination.



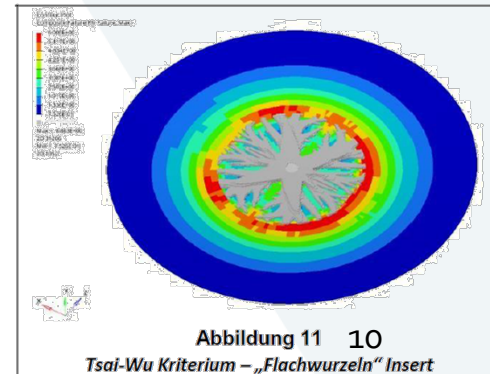
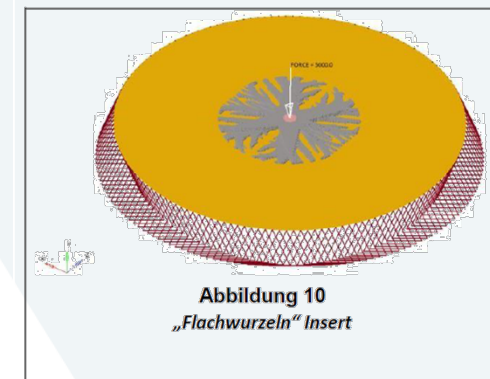
Project results - process calibration, simulation & distortion control

- **Process simulation & calibration:** used simulation tools (SimSolver) and cantilever benchmarks to predict distortions and refine scanning / support strategies for fine beams, reducing trial-and-error during production.
- **Benefit:** simulation-guided pre-processing reduced rework and enabled more accurate conversion of lattice beam elements into printable solids while keeping overall element counts manageable.



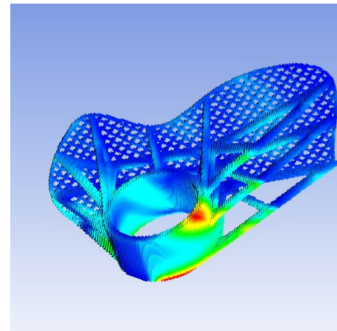
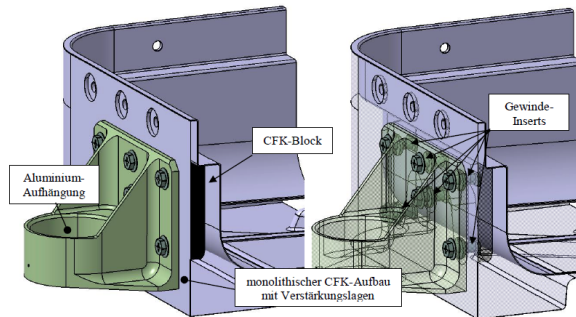
Project results - topology & lattice optimisation — the digital toolbox

- **Method:**
 - multi-objective optimisation targeted minimisation of composite failure criterion (Tsai-Wu) rather than simply minimising connection stress
 - generated geometry families for axial, shear, bending and combined loads.
- **Deliverable:**
 - digital element-toolbox of parametrised bionic, lattice and hook geometries (CAD + FEM), enabling selection of element types by load case and manufacturing limits.



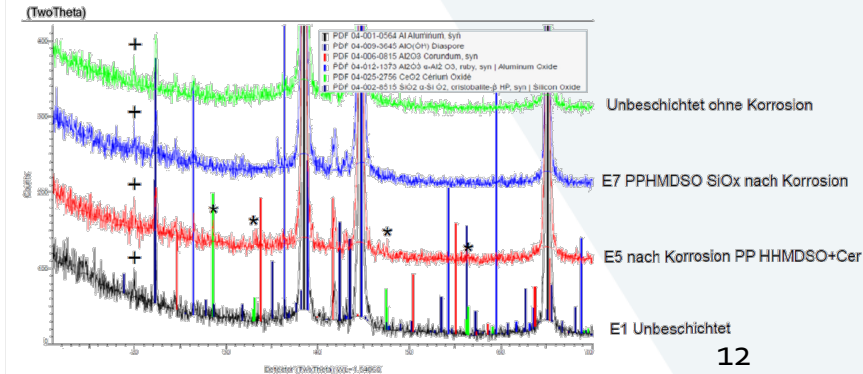
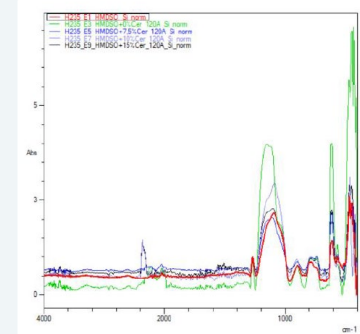
Project results - demonstrator CAD, bracket design & optimisation workflow

- **Workflow:** CAD → topology optimisation → conversion of beam lattices to printable solids (3-matic) → process simulation → SLM printing → APPD coating → lamination (iterative loops addressed printability and lamination constraints)
- **Example outcome:** optimised bracket geometries that replace heavier CFK/aluminium assemblies while matching stiffness and reducing local laminate stresses.



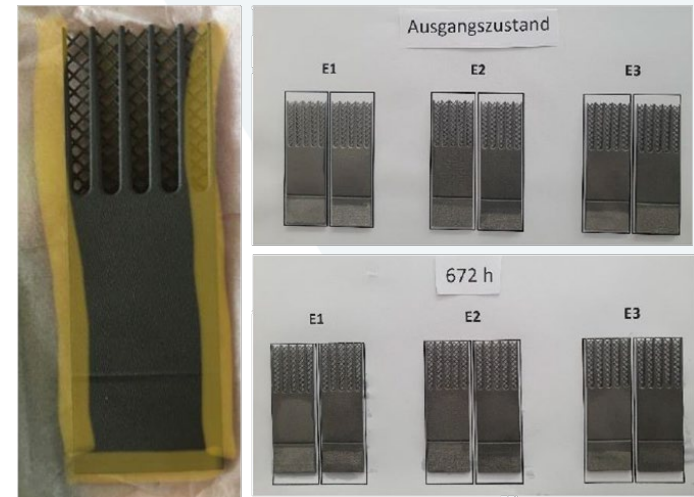
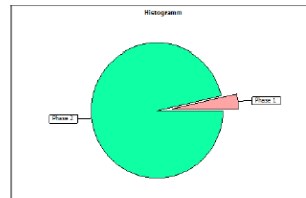
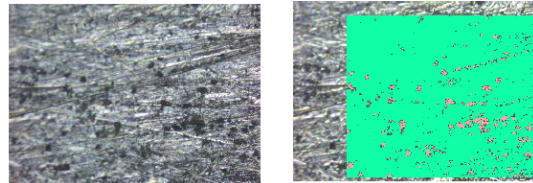
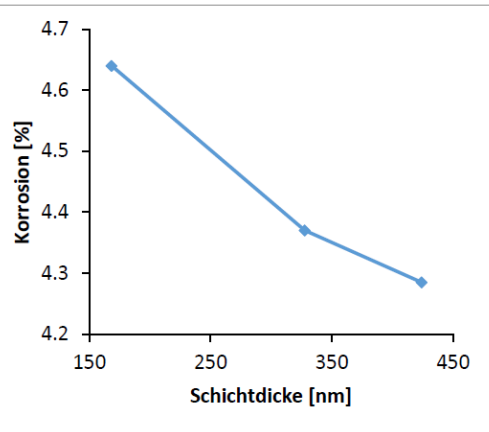
Project results - APPD coatings for adhesion & active corrosion protection

- **Coating approach:** atmospheric pressure plasma deposition of HMDSO-based films, with aerosol doping using cerium salts ($\text{Ce}(\text{NO}_3)_3$) to attempt active corrosion inhibition and to modify wettability for epoxy adhesion.
- **Key findings:**
 - coating thickness and wettability can be varied with process current and aerosol composition
 - higher carbon content at lower deposition currents (organic-rich films)
 - Ce signal detectable at low atomic % in some samples



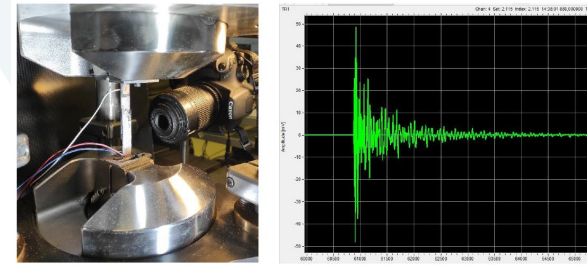
Project results - corrosion resistance & longevity evidence

- Salt-spray tests:
 - coated Ti-6Al-4V SLM samples exposed to 672 h salt spray showed no visible corrosion



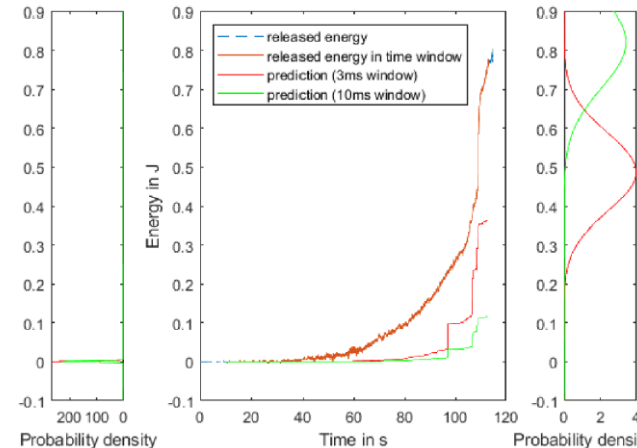
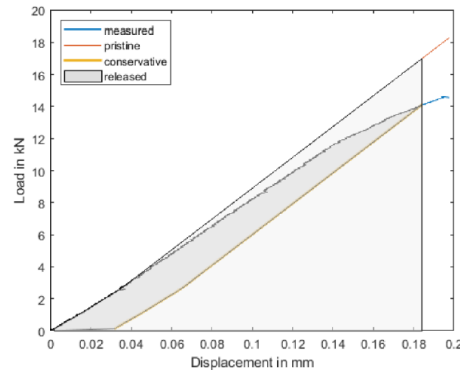
Project results - SHM: method selection & test-programme definition

- **Selection process:** literature survey and experimental screening identified Acoustic Emission (AE) and Electrical Impedance (EI) as most promising for detecting damage progression in the small, well-defined interfacial region of inserts.
- JKU defined coupon geometries for in-plane shear and out-of-plane peeling, integrated sensor layouts and data-collection protocols to correlate AE/EI signals with mechanical energy release.



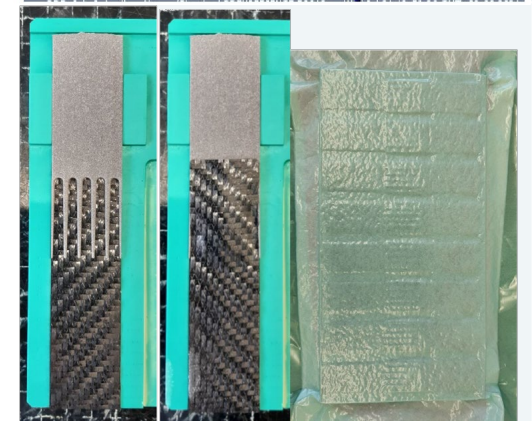
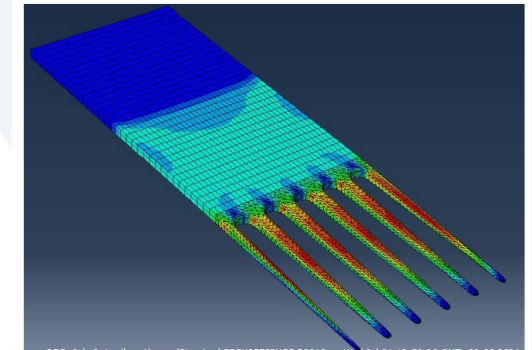
Project results - SHM data processing → damage quantification

- **Analytical advance:** developed an approach to estimate released mechanical energy from force-displacement curves and correlate it probabilistically with AE energy to derive a damage parameter for overlap joints.
- **Practical implication:** while AE energy vs released energy shows scatter, statistical/training-based methods produce useful probabilistic damage estimates enabling level-1 detection and level-3 assessment (Rytter levels).



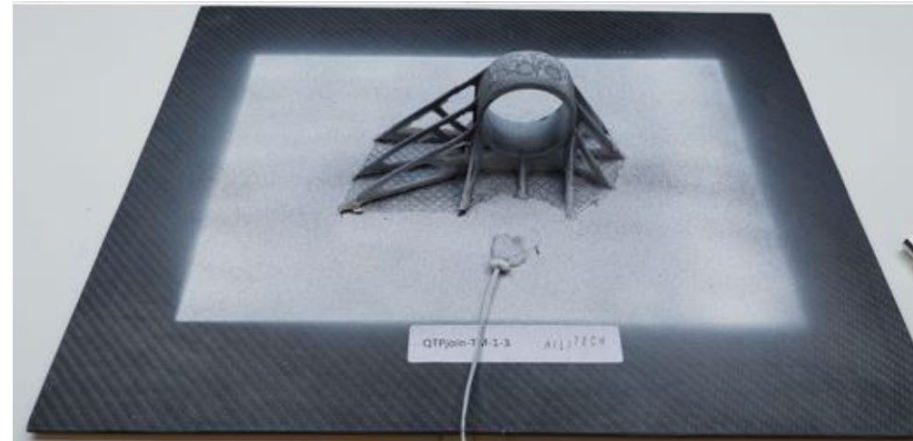
Project results - coupon testing — lap-shear, pull-out and shear protocols

- **Test programme:** standardised tests (pull-out, in-plane shear, lap-shear) executed on both real and optimised insert variants, with defined speed (2 mm/min), photographic documentation and retention of broken specimens for forensic analysis.
- **Outcomes:** established repeatable test procedures and integration of SHM sensors during quasi-static tests to build correlations between mechanical behaviour and AE/EI signals.



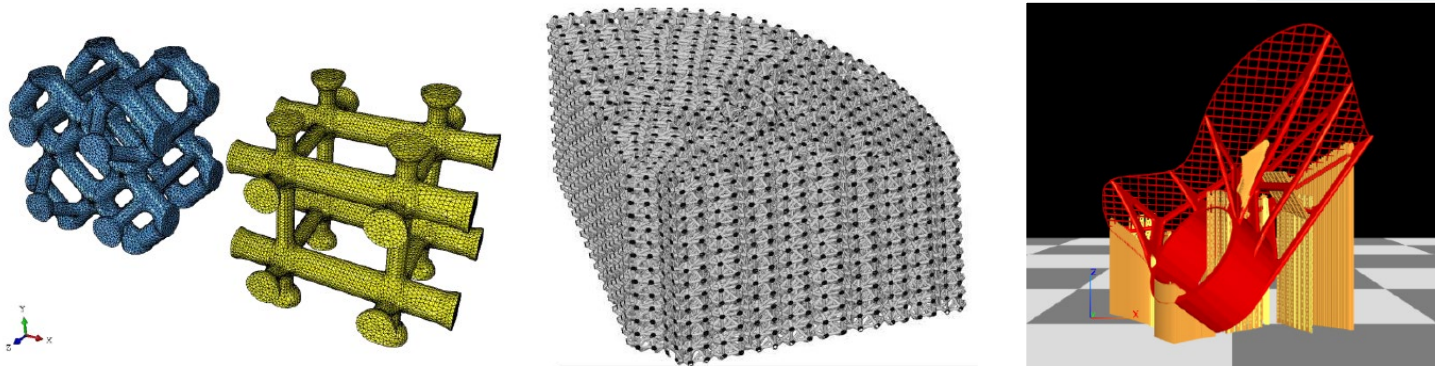
Project results - demonstrator test series (monolith & sandwich)

- **Demonstrators:** two parallel demonstrators — Demonstrator 1 (monolithic CFK) and Demonstrator 2 (CFK sandwich) — defined by HiLiTECH to cover different design philosophies and load scenarios.
- **Test execution:** series of static tests with SHM capture, DIC where used, and direct comparison of real vs optimised inserts to quantify stress redistribution and load capacity changes.



Project results - mechanical performance highlights & improvements

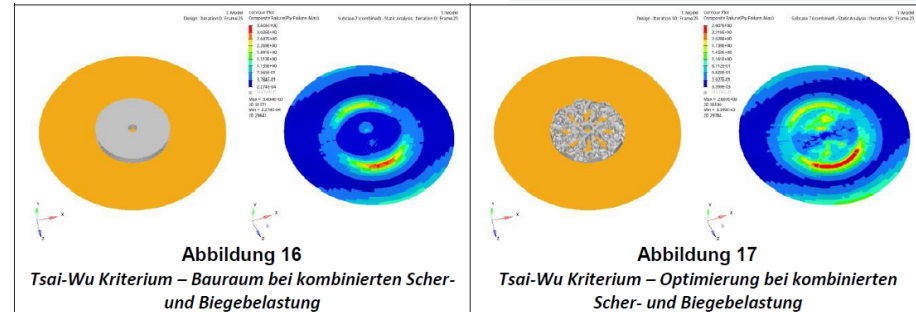
- **Quantified benefit:** topology optimisation reduced the maximum Tsai-Wu laminate failure index (example: 1.19 \rightarrow 0.93 in shear case), indicating meaningful reduction in composite failure risk for optimised pads.
- **Engineering impact:** lattice inserts better match laminate compliance and reduce local laminate stresses, offering a direct pathway to increased allowable loads and improved fatigue performance in hybrid joints.





Utilization of the project - demonstrators → near-term industrial uptake

- **Immediate use:**
 - validated workflow for tuned inserts is applicable to aircraft interiors and UAV structures where weight saving and in-service inspectability are priorities
 - the digital element toolbox allows customised inserts per load case.
- **Value proposition:**
 - lower laminate failure risk, simplified retrofitting and targeted weight savings compared to traditional fastened solutions.

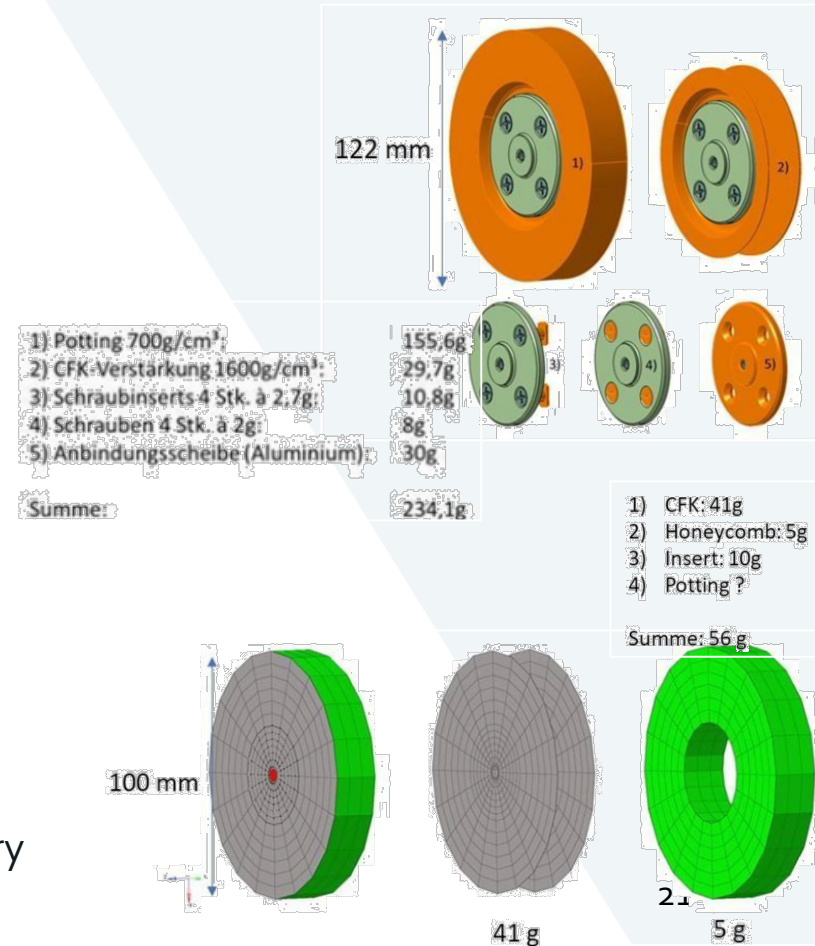


Utilization of the project - inspectability, maintenance & SHM benefits

- **Inspectability:**
 - integrated AE/EI monitoring enables non-destructive, in-service health checks of embedded inserts
 - probabilistic damage metrics support maintenance decision making and may reduce inspection intervals/costs.
- **Maintenance & certification:**
 - SHM evidence (damage detection + energy correlation) strengthens the certification dossier by providing objective operational monitoring data.

Further steps / follow-up projects

- **Next technical steps:**
 - complete fatigue campaigns to quantify lifetime gains under representative spectrum loading,
 - produce TRL₅ pilot parts and perform environmental/fatigue/certification tests,
 - refine coating → lamination adhesion studies for final prototypes
- **Commercial / research follow-ups:**
 - scaling to larger brackets, integration with repair/cold-cure resin systems
 - LCA and end-of-life assessments
 - formal certification pathway planning with industry partners and regulators.



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