Polymer Composites

TUHH
Hamburg University of Technology

SIMULATION OF THE PROGRESSIVE FAILURE OF CFRP AT ELEVATED TEMPERATURE

Johann Körbelin, Nilas Junge, Michael Skrzypczak, Bodo Fiedler

Hamburg University of Technology
Institute of Polymers and Composites
Denickestraße 15, D-21073 Hamburg, Germany

ICCM23 – Belfast, 2023

Temperature Dependency of CFRP

- Composite structures are (unavoidably) subjected to various (elevated) temperatures during service

- Epoxy matrix material properties decline with temperature

- UD CFRP with increasing temperature

E_1, X_T	→
E_2, G_{12}	↓
X_C, Y_T, Y_C, S_L	↓
G_{IC}	→ / ↗
G_{IIC}	→

- The effect of elevated temperature on failure is hard to predict → combination of a multitude of influencing factors

[Airbus]

[Polestar]

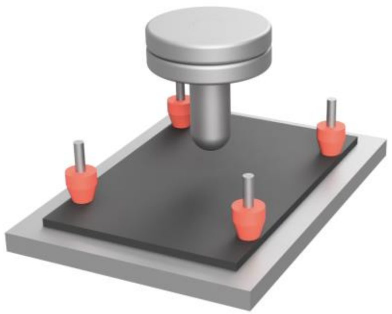
The matrix's mechanical performance decreases with increasing environmental temperature and negatively influences the damage tolerance.

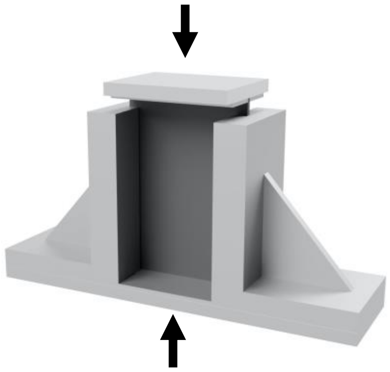
Temperature Dependency of Damage Tolerance: Approach

Determination of Impact Resistance and Residual Strength

UD-Prepreg: Hexcel HexPly M21/T800s 265 g/m^2
Tg: 171 °C (Onset)

Layup: $[45/0/-45/90]_{2s}$
Laminate Thickness: 4.1 mm



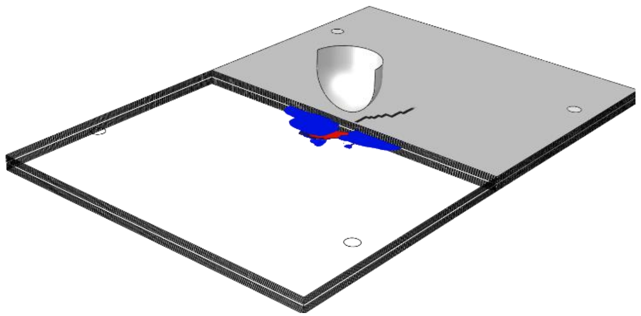


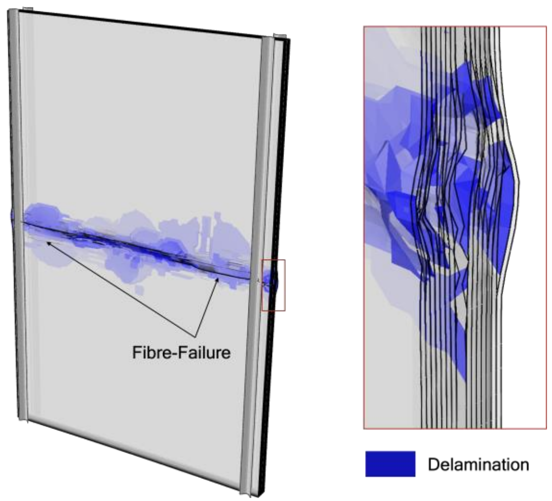
ASTM D7136 M
Impact Parameters:
Energy: 15-21 J
Temperature: 20 °C – 80 °C

ASTM D7137 M
Temperature: 20 °C + 80 °C

Simulation of LVI and CAI at Elevated Temperature

- Mechanical characterisation of M21/T800s at temperatures between 20 °C and 100 °C
- Implementation of temperature dependency into the Continuum Damage code CompDam
- Simulation of LVI and CAI under temperature influence with Abaqus/Explicit

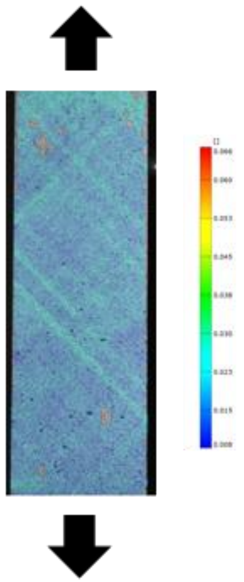




CompDam, v2.5.0, F. A. Leone, A.C. Bergan and C G. Dávila, https://github.com/nasa/CompDam_DGD, 2019

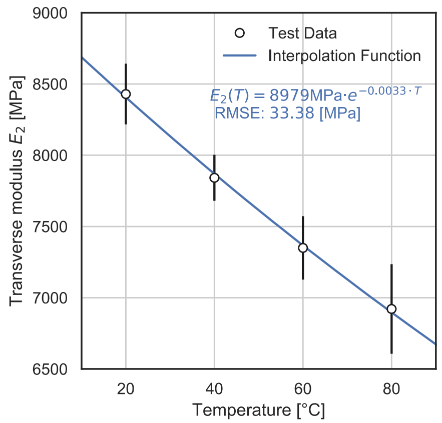
Temperature Dependency of Damage Tolerance: Approach Simulation

Material Characterisation

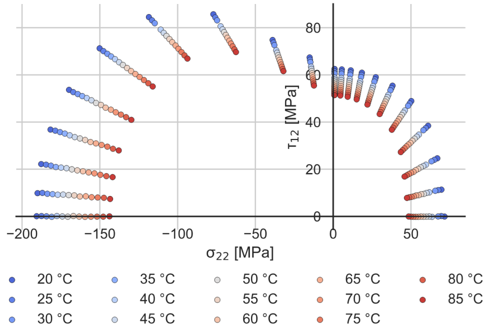


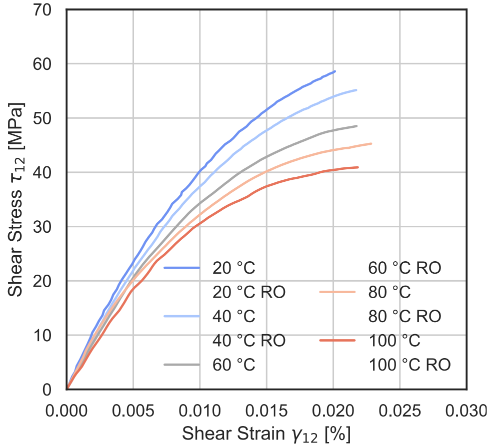
Coupon Testing at
20°C -100 °C

Interpolation Functions



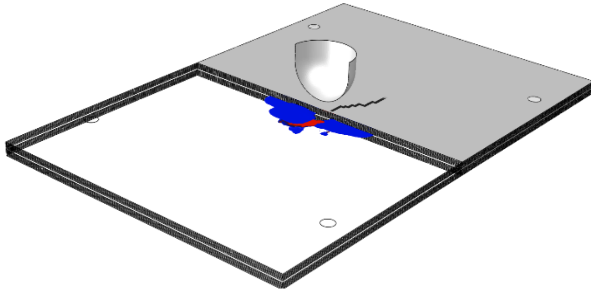
Implementation into CDM and Single Element Testing

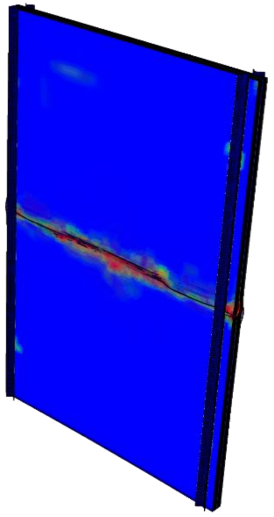




CDM is based on CompDam

LVI and CAI Simulation





Abaqus/Explicit

Temperature Dependency of Damage Tolerance: Material Characterisation

Stress-free temperature: 171 °C (determined with a bistable laminate)

Mechanical Properties

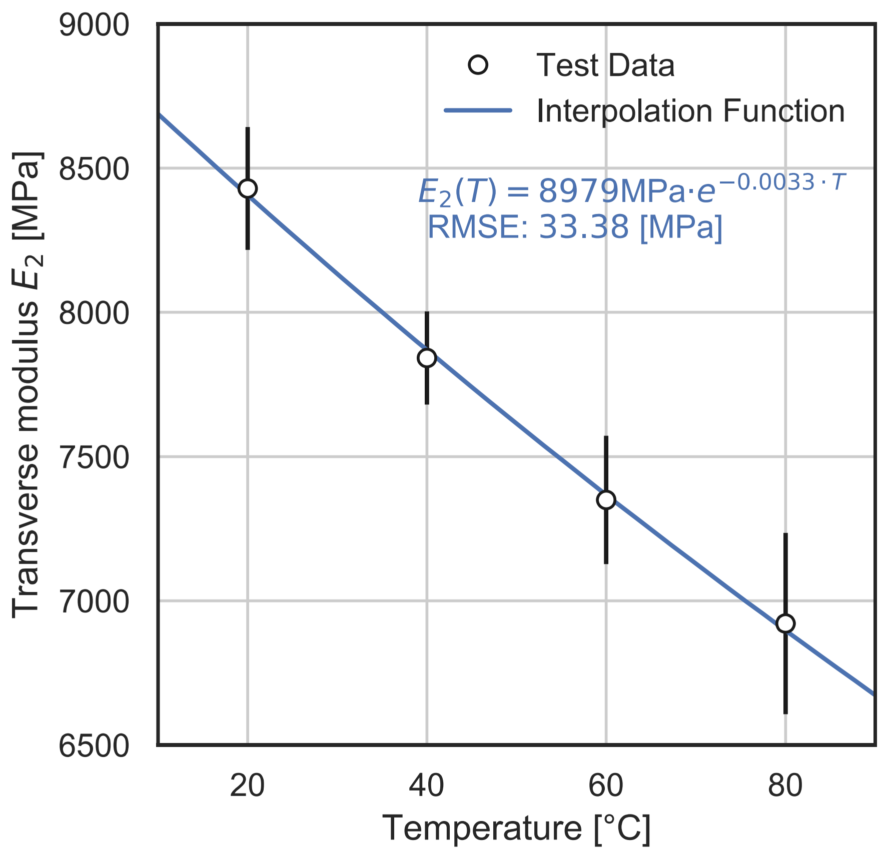
Temperatures: 20 °C - 100 °C

Tensile Tests: E_1, X_T, $E_2(T)$, $Y_T(T)$.	ASTM D 3039
Compression Tests: $Y_C(T)$, $X_C(T)$,	ASTM D 6641
Shear Tests: $G_{12}(T)$, $S_L(T)$	ASTM D 3518

Interlaminar Properties:

Temperature: 20 °C

Mode I: G_{IC}	ASTM D 5528
Mode II: G_{IIC}	ASTM D 7905



Material Model: Failure

CDM is based on CompDam

Fibre Failure:

Tension (Temperature independent):

Damage initiation: Max-stress criterion

Damage propagation: Bi-linear energy based degradation

Compression:

Damage initiation: Temperature dependent max-stress criterion

Damage propagation: Temperature independent
Bi-linear energy based degradation

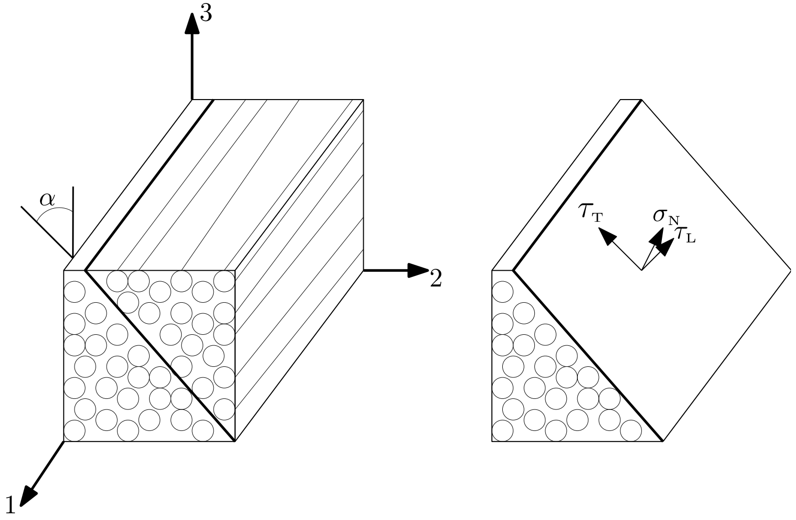
Matrix Failure:

Damage initiation:

- Temperature dependent
- Accounts for friction on fracture plane

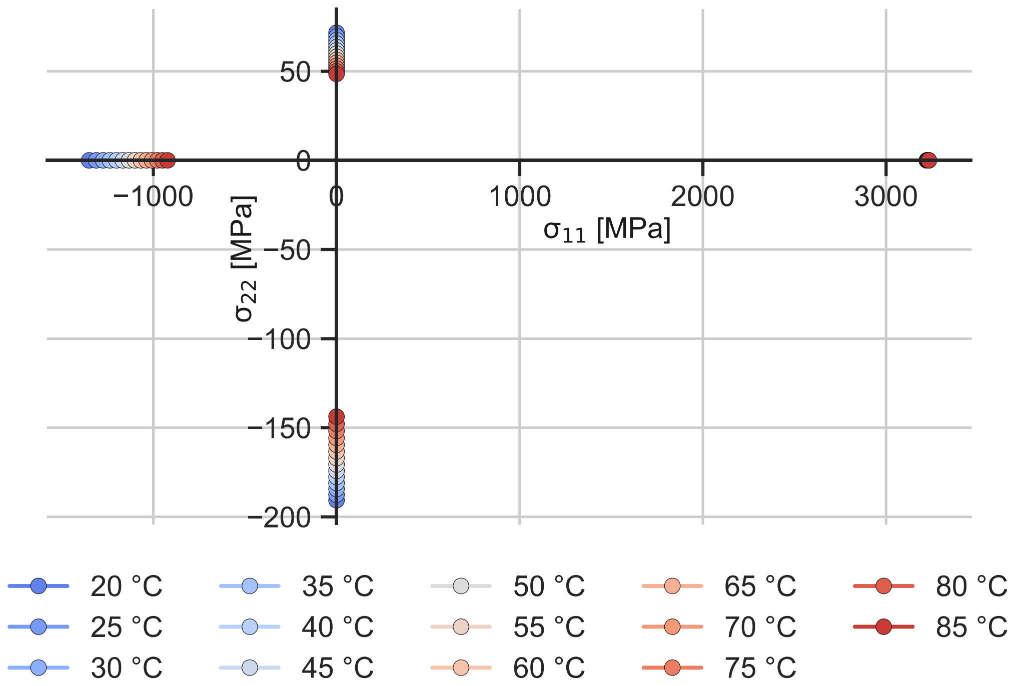
Damage Propagation:

- Temperature independent Benzeggagh-Kenane Law

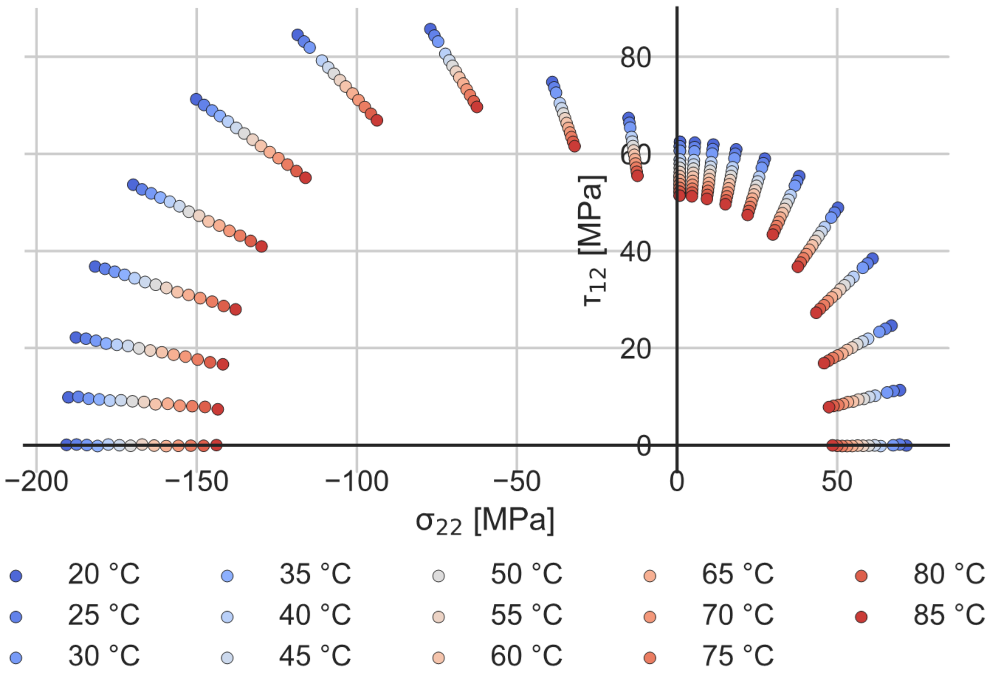


Single-Element Tests: Temperature-Dependent Failure Envelope

$\sigma_{11} - \sigma_{22}$ Plane



$\sigma_{22} - \tau_{12}$ Plane

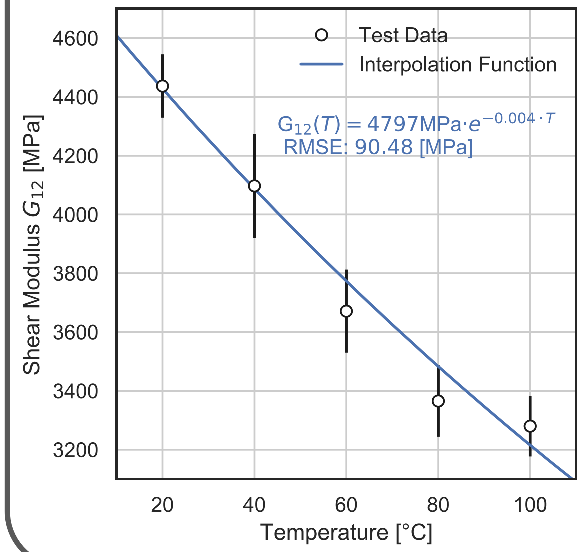


Material Model: Shear Nonlinearity

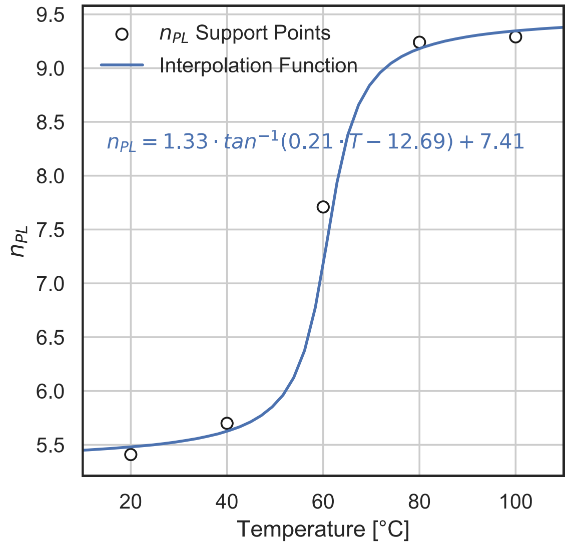
Non-linear shear behaviour is represented by the Ramberg-Osgood equation:

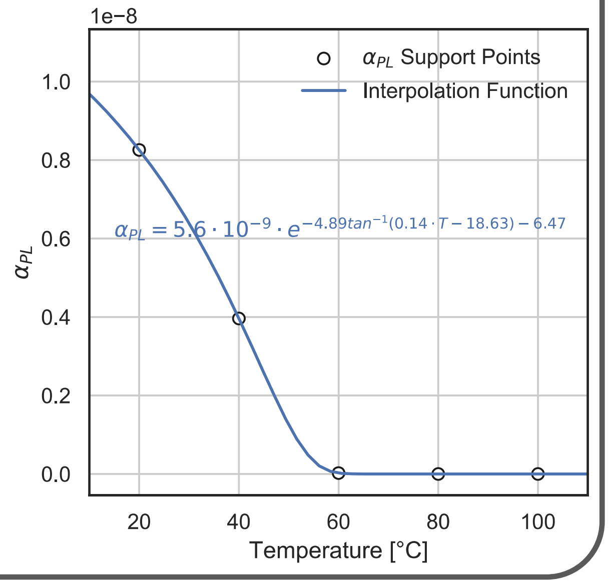
$$\gamma_{12} = \frac{\tau_{12} + \alpha_{PL(T)} sign(\tau_{12}) |\tau_{12}|^{n_{PL}(T)}}{G_{12}(T)}$$

Shear Modulus

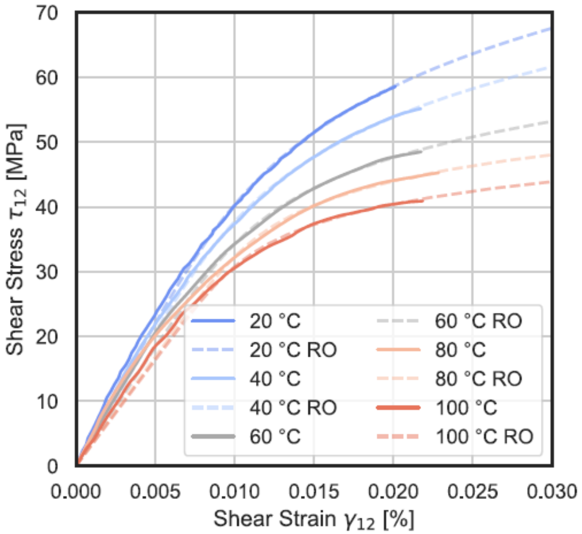


Ramberg-Osgood Parameter





Shear Response



Material Model: Delamination modelling

Abaqus Cohesive Contact

Quadratic Stress Initiation Criterion:

$$\left(\frac{\langle t_\mathrm{n}\rangle}{t_\mathrm{n}^0(T)}\right)^2 + \left(\frac{t_\mathrm{l}}{t_\mathrm{l}^0(T)}\right)^2 + \left(\frac{t_\mathrm{t}}{t_\mathrm{t}^0(T)}\right)^2 \geq 1$$

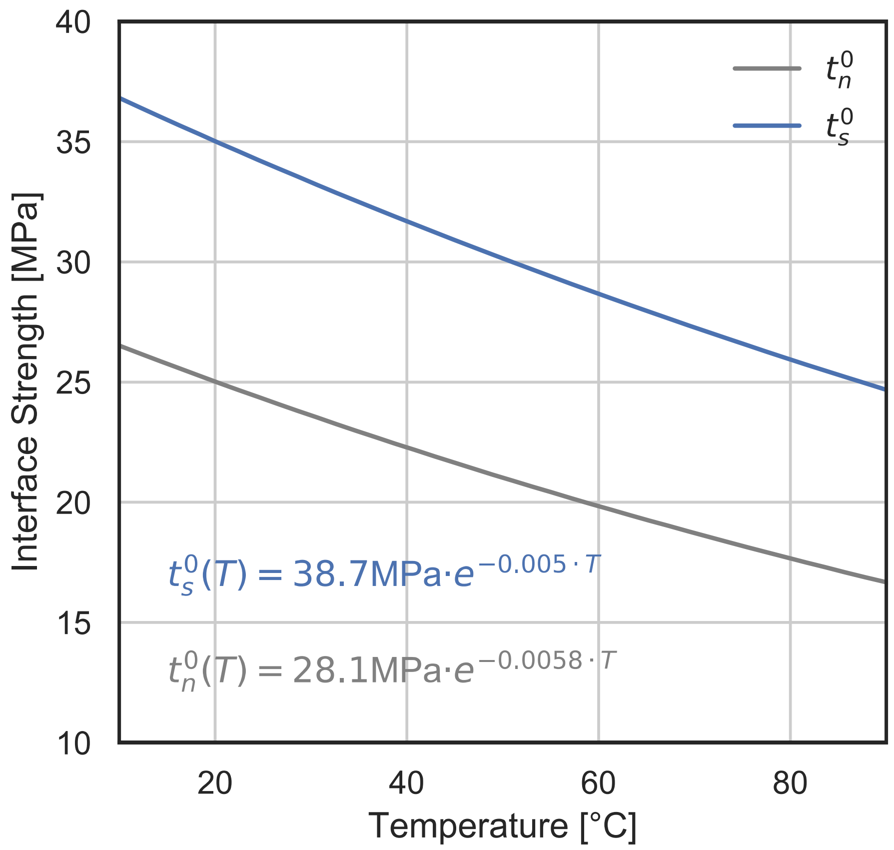
Qualitative interface strength degradation is coupled to experimental values:

Mode I initiation to Y_T

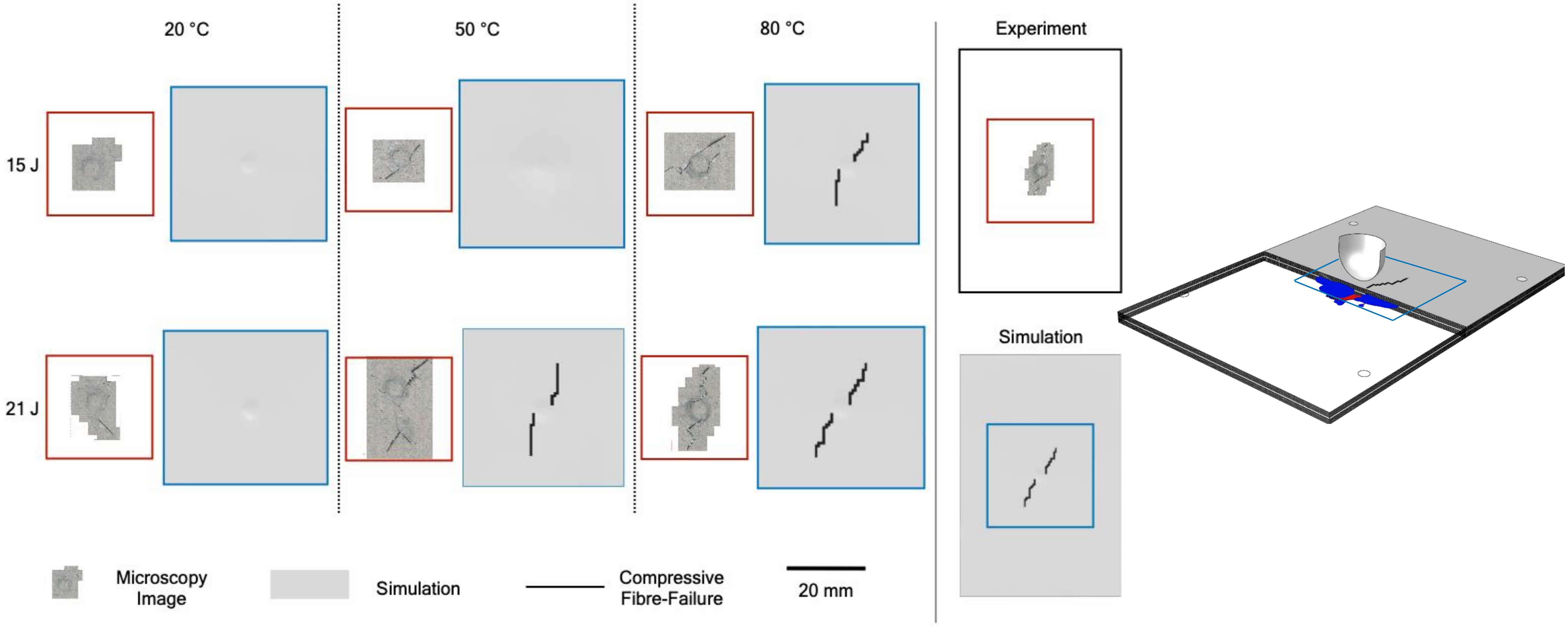
Mode II initiation to S_T

Degradation:

Temperature independent Benzeggagh-Kenane Law

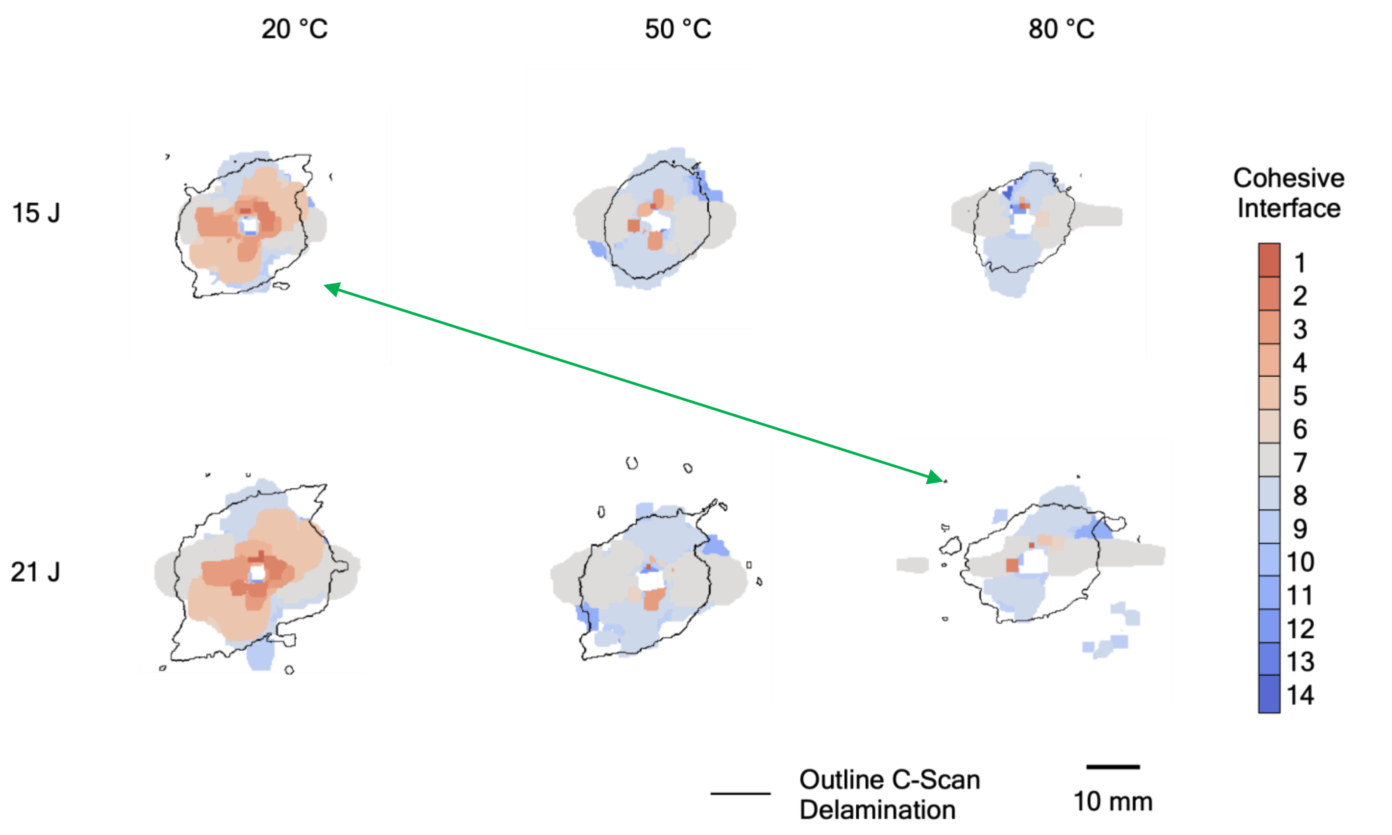


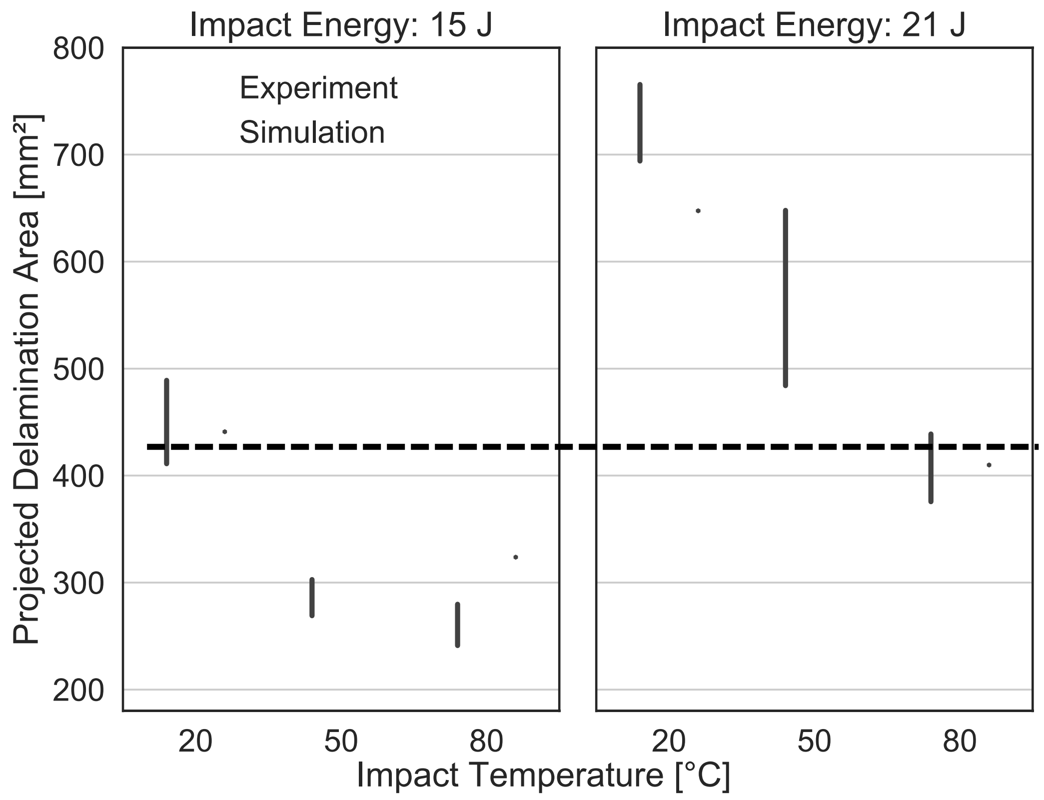
Low Velocity Impact: Top Layer Damage



With increasing temperature failure modes change:
Severe fibre failure occurs.

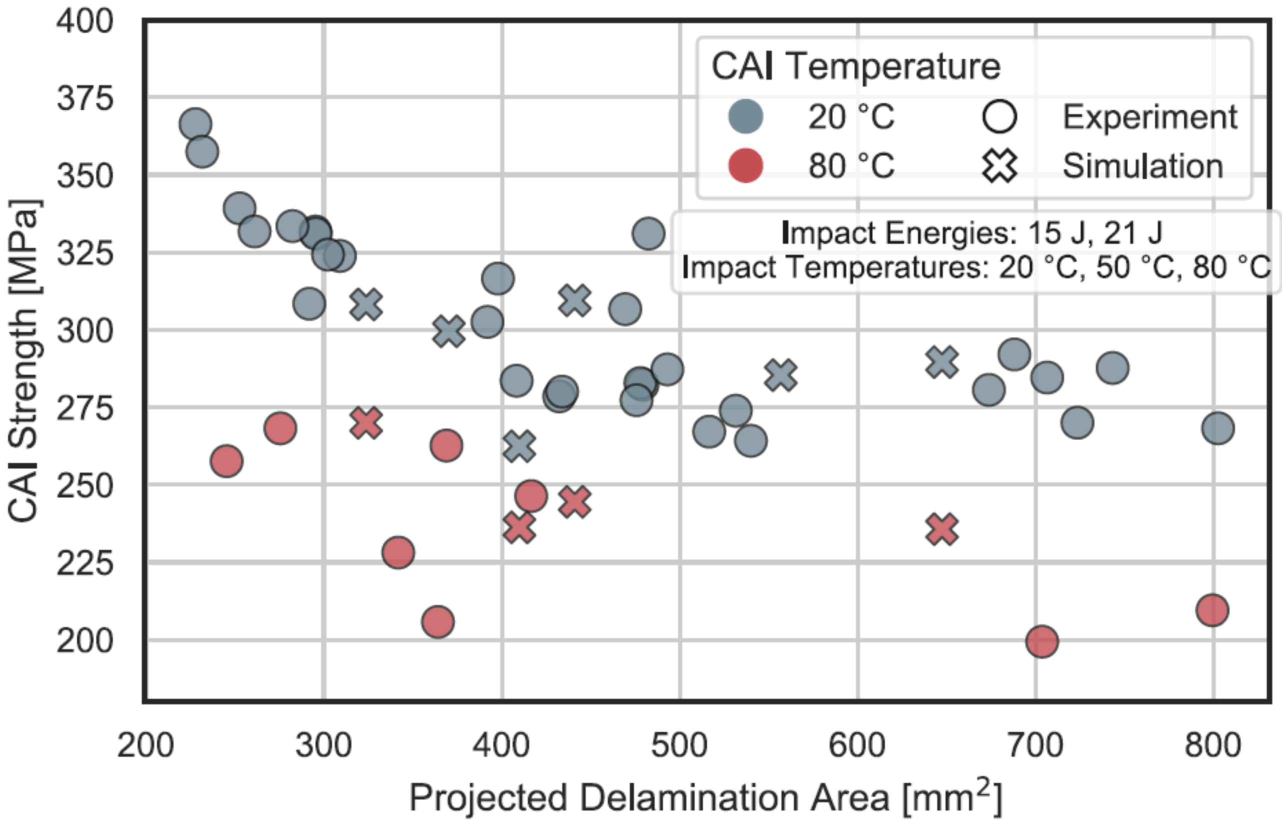
LVI: Delamination Damage

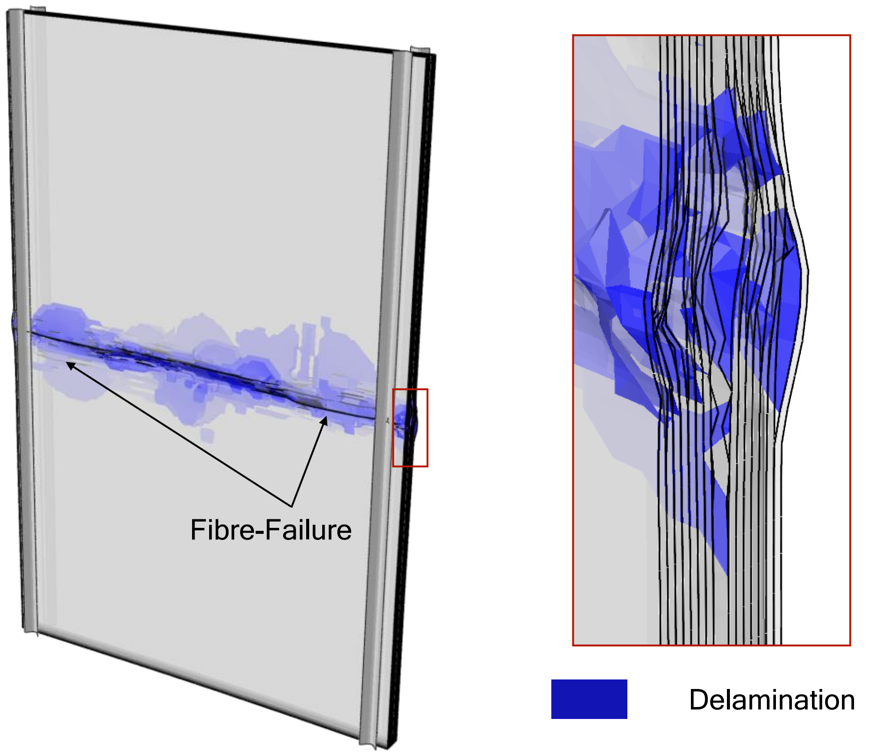




At different temperatures, different impact energies can result in the same delamination area.

CAI: Residual Strength



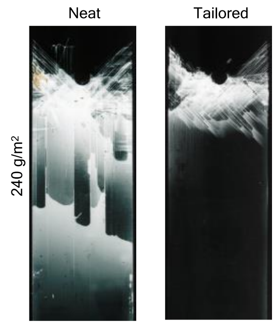


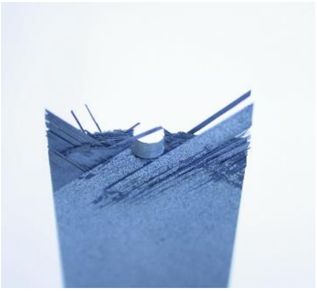
Temperature has a more decisive influence on the compressive residual strength than the impact parameters.

Research Hypothesis

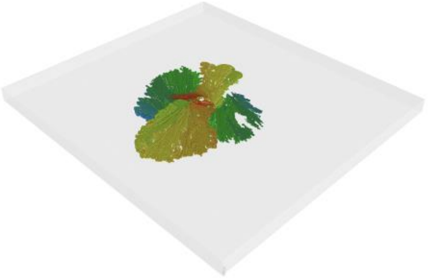
Understanding and adapting the matrix's damage behaviour is fundamental to improve the damage tolerance of high-performance composites.

The addition of carbon nanoparticles into the matrix introduces additional energy-consuming damage mechanisms and increases the damage tolerance.

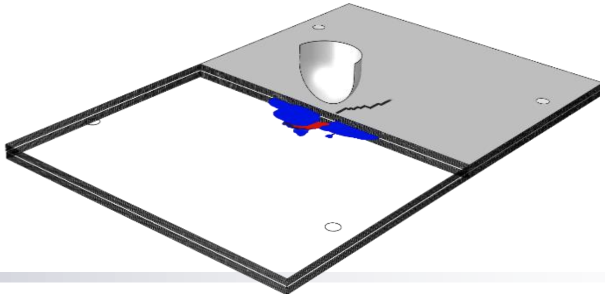


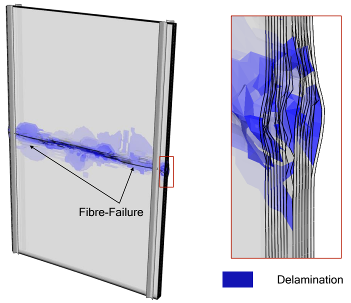


The composite's layup can control the occurring matrix damage modes. Thin-ply, bio-inspired helicoidal layups enable delamination-free composites.



The matrix's mechanical performance decreases with increasing environmental temperature and negatively influences the damage tolerance.





Peer Reviewed Publications

Modelling of Low-Velocity-Impact and Compression-After Impact of CFRP at Elevated Temperatures, J Körbelin, N Junge, B Fiedler, Composites Part A, Accepted, 2021

Damage Tolerance and Notch Sensitivity of Bio-Inspired Thin-Ply Bouligand Structures, J Körbelin, P Goralski, B Kötter, F Bittner, H-J Endres, B Fiedler, Composites Part C: Open Access, 2021

Damage tolerance of few-layer graphene modified CFRP: from thin- to thick-ply laminates, J Körbelin, B Kötter, H Voormann, L Brandenburg, S Selz, B Fiedler, Composites Science and Technology, 2021

Impact of temperature on LVI-damage and tensile and compressive residual strength of CFRP, J Körbelin, C Dreiner, B Fiedler, Composites Part C: Open Access 3, 100074, 2020

Influence of temperature and impact energy on low-velocity impact damage severity in CFRP, J Körbelin, M Derra, B Fiedler, Composites Part A: Applied Science and Manufacturing 115, 76-8, 2020

CFRP thin-ply fibre metal laminates: Influences of ply thickness and metal layers on open hole tension and compression properties, B Kötter, J Karsten, J Körbelin, B Fiedler, Materials 13 (4), 910, 2020

Carbon Nanoparticles' Impact on Processability and Physical Properties of Epoxy Resins—A Comprehensive Study Covering Rheological, Electrical, Thermo-Mechanical, and Fracture Properties (Mode I and II), H Meeuw, J Körbelin, VK Wisniewski, AS Nia, AR Vázquez, MR Lohe, X Feng, B Fiedler, Polymers 11 (2), 231, 2018

Acknowledgements