Isothermal fatigue behavior of metal/CF hybrid composites with potential for intrinsic structural health monitoring

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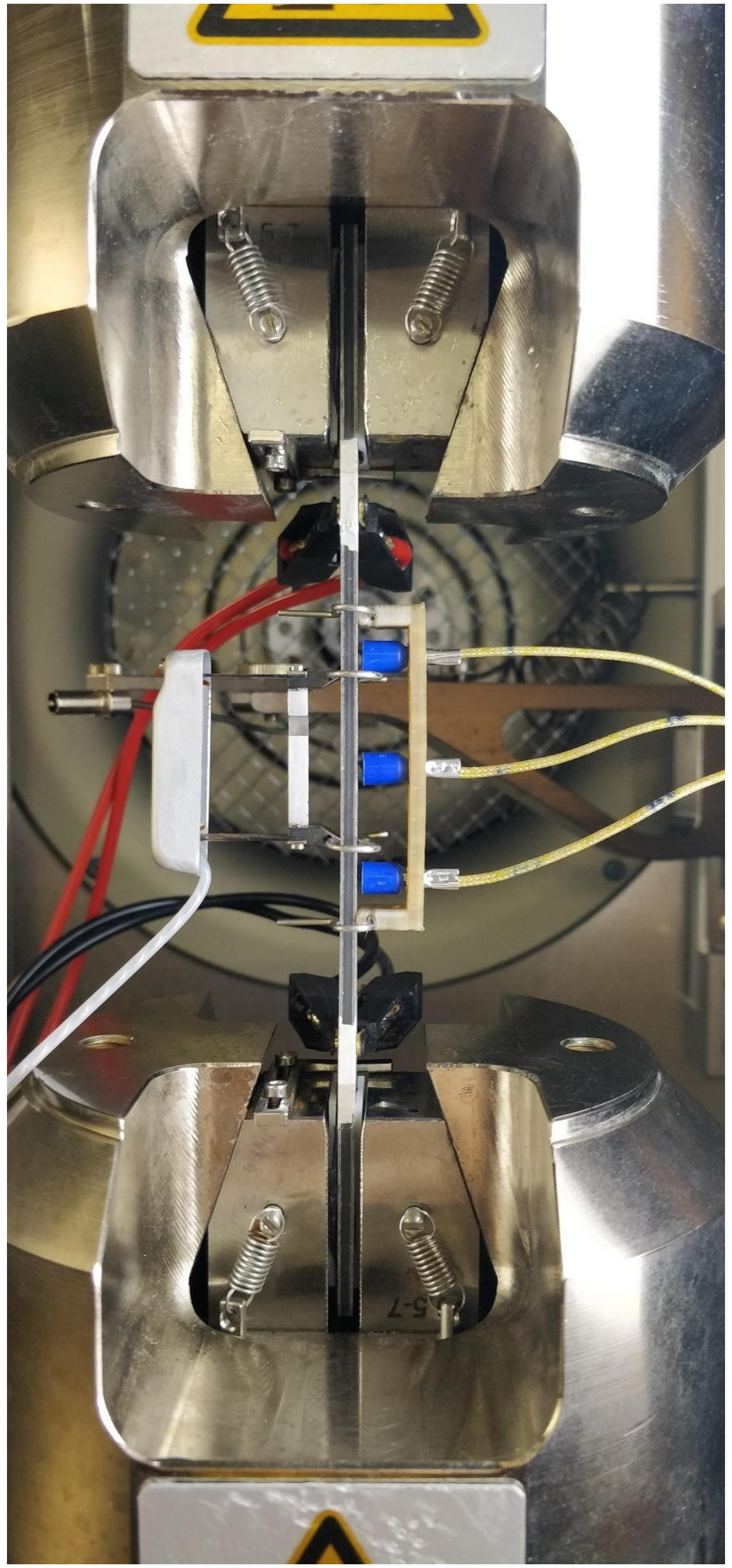


MOTIVATION

Metal/carbon-fiber hybrid composites (MCFRPs)

WHY COMBINE METALLIC AND CARBON FIBERS

- The rigidity of CF together with the ductility and electrical conductivity of metals

- MCFRPs can intrinsically realize aircraft functions such as impact tolerance, signal transport, lightning-strike protection

METASTABLE AUSTENITIC STAINLESS STEEL FIBERS

- More ductility and damage tolerance in the composite
- Additional functionality through improved electrical conductivity
- Possibility of non-destructive structural health monitoring (SHM) through the austenite-martensite phase transformation

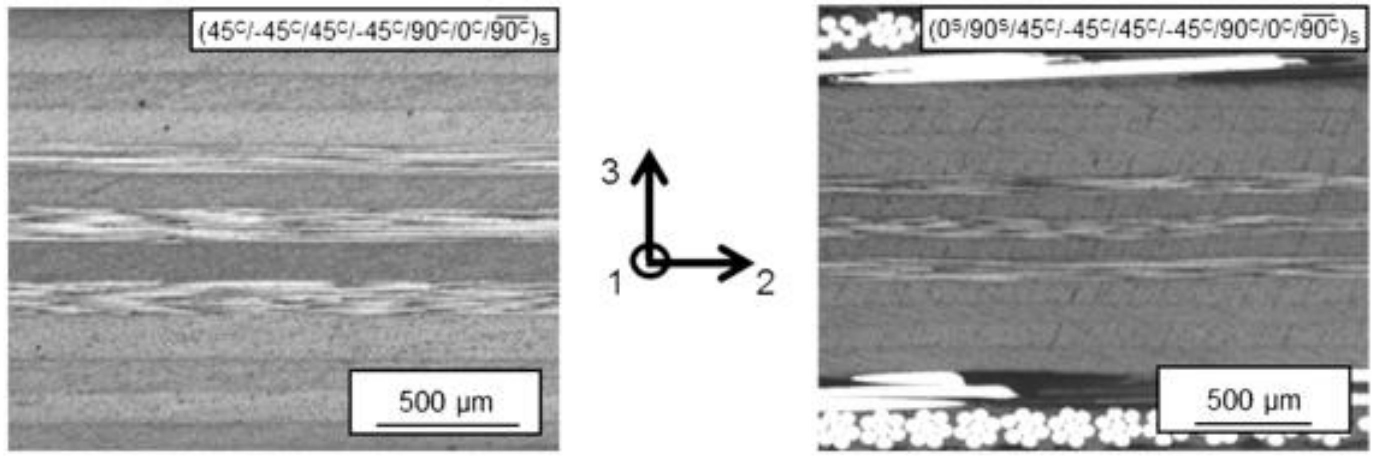
- Characterization of isothermal fatigue behavior necessary to validate SHM method at aviation standard testing temperatures

PROJECT OBJECTIVE

Isothermal fatigue characterization of CFRP and MCFRP

FOLLOW-UP TO A PREVIOUS PROJECT

- Optimal MCFRP laminate layup determined
- Multi-directional layup with stainless steel fibers on the periphery

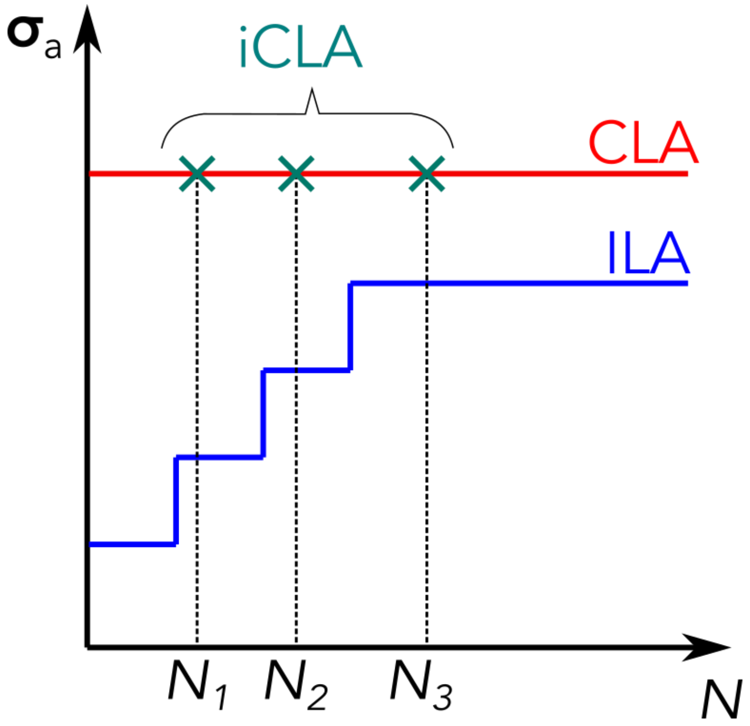


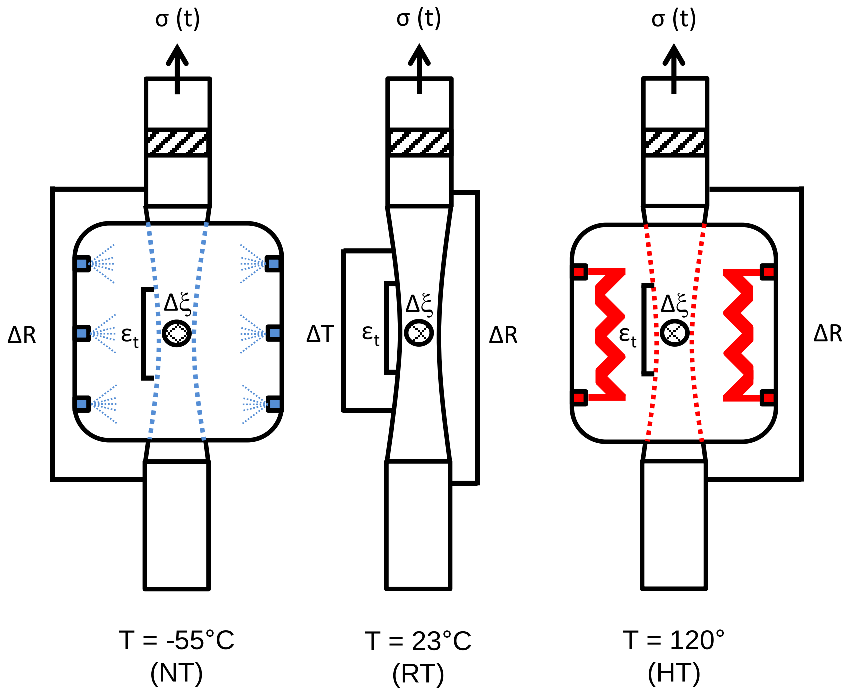
Backe et al., 2018 [1]

ISOTHERMAL FATIGUE CHARACTERIZATION

- In the LCF and HCF regimes, up to 2×10^6 loading cycles at RT, -55°C and +120°C with R = 0.1
- Constant and increasing load-amplitude tests (CLA & ILA)
- Microscopy and crack propagation analysis

- Simultaneous monitoring of
  - Surface temperature
  - Electrical resistance
  - Magnetic response due to deformation-induced martensitic phase transformation





MATERIALS AND METHODS

Laminate fabrication and sample preparation

FABRICATION AT TU KAISERSLAUTERN

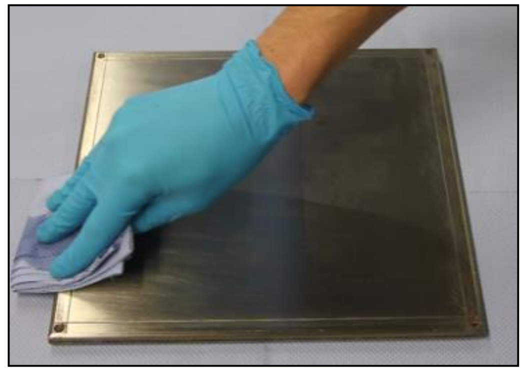
- Autoclave process to fabricate CFRP and MCFRP plates
  - Diameters: 7 µm carbon fiber bundles, 70 µm steel fibers
- Samples cut from plates using water-jet cutting

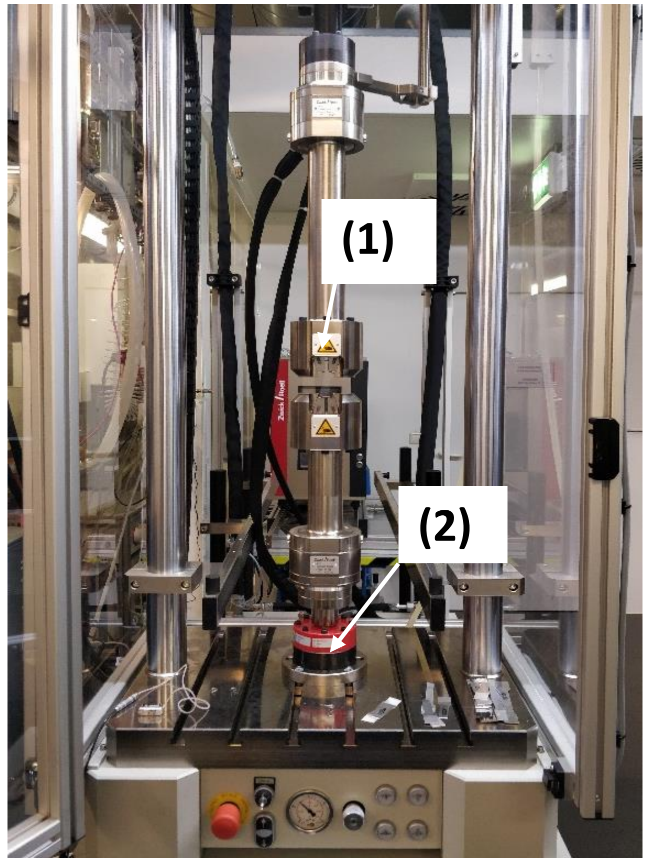
TESTING SETUP

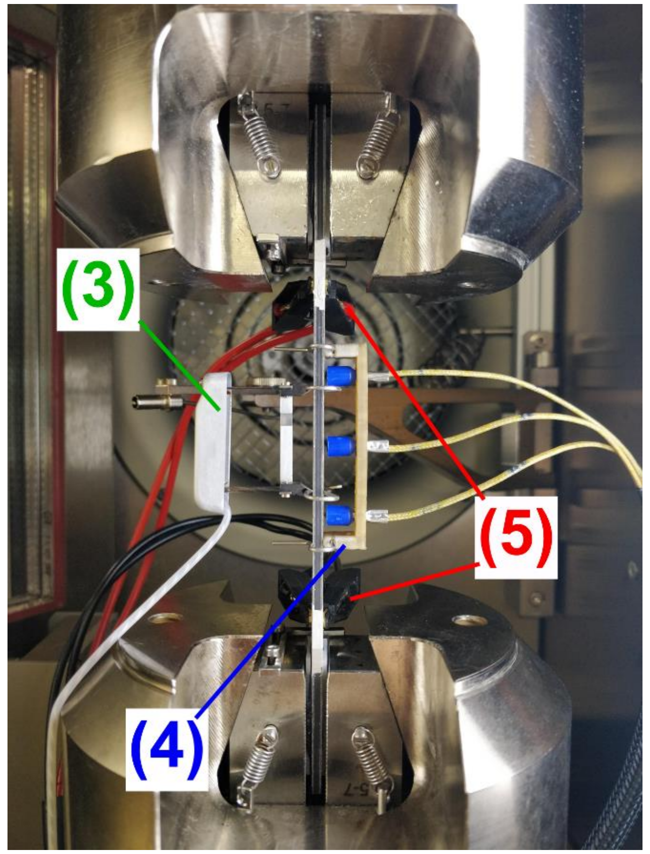
- Zwick/Roell HC-25 servo-hydraulic testing machine (F_{max} = 25 kN), equipped with:
- (1) pressurized sample clamps, (2) force sensor, (3) strain gauge, (4) thermocouples, (5) 4-point resistance measurement
- Ferritscope to measure martensite content of steel fibers in MCFRP

FATIGUE TESTING PARAMETERS

- R = 0.1
- Up to 2×10^6 cycles
- f = 5 Hz (RT and 120 °C), f = 10 Hz @ -55 °C

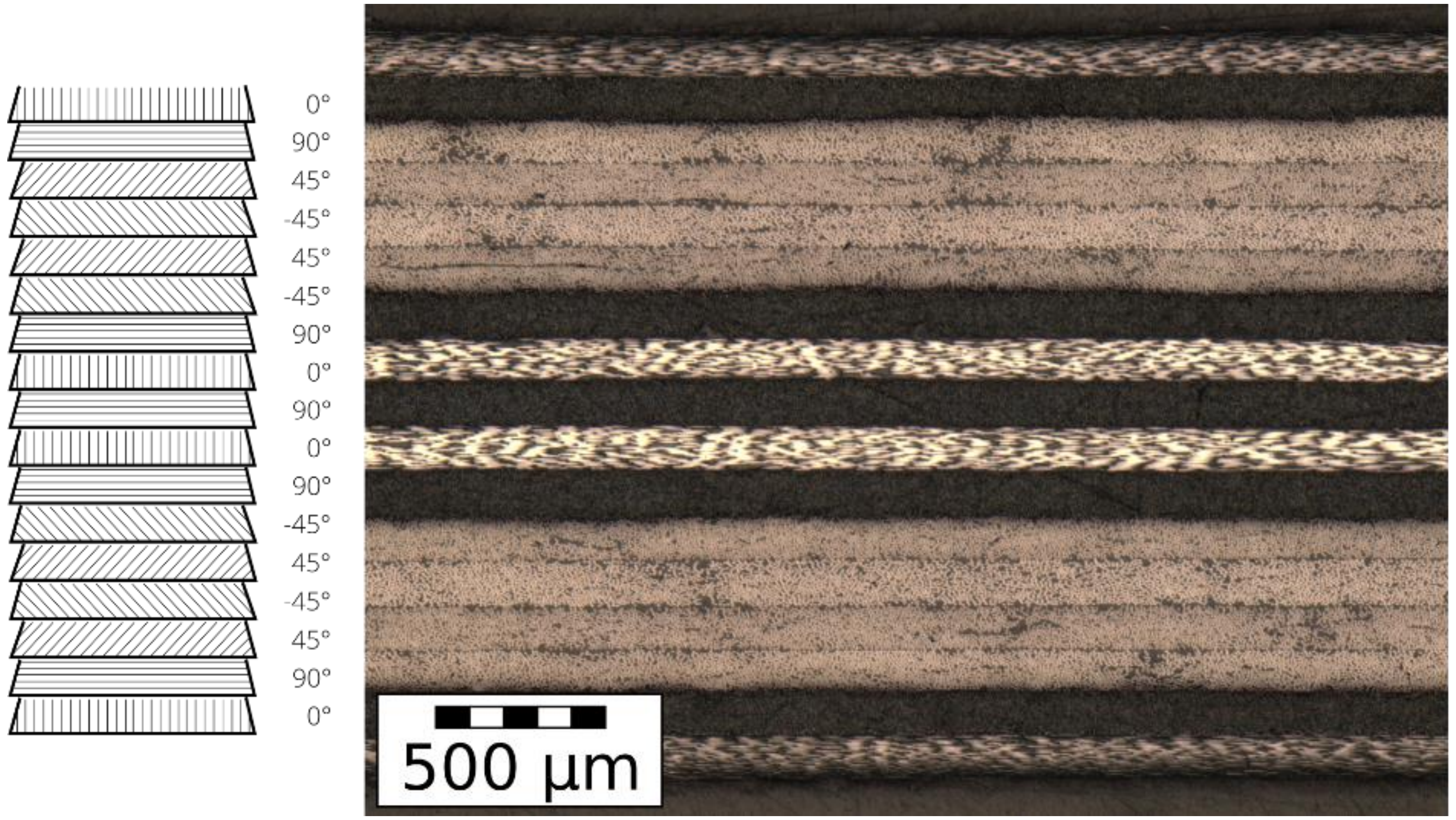




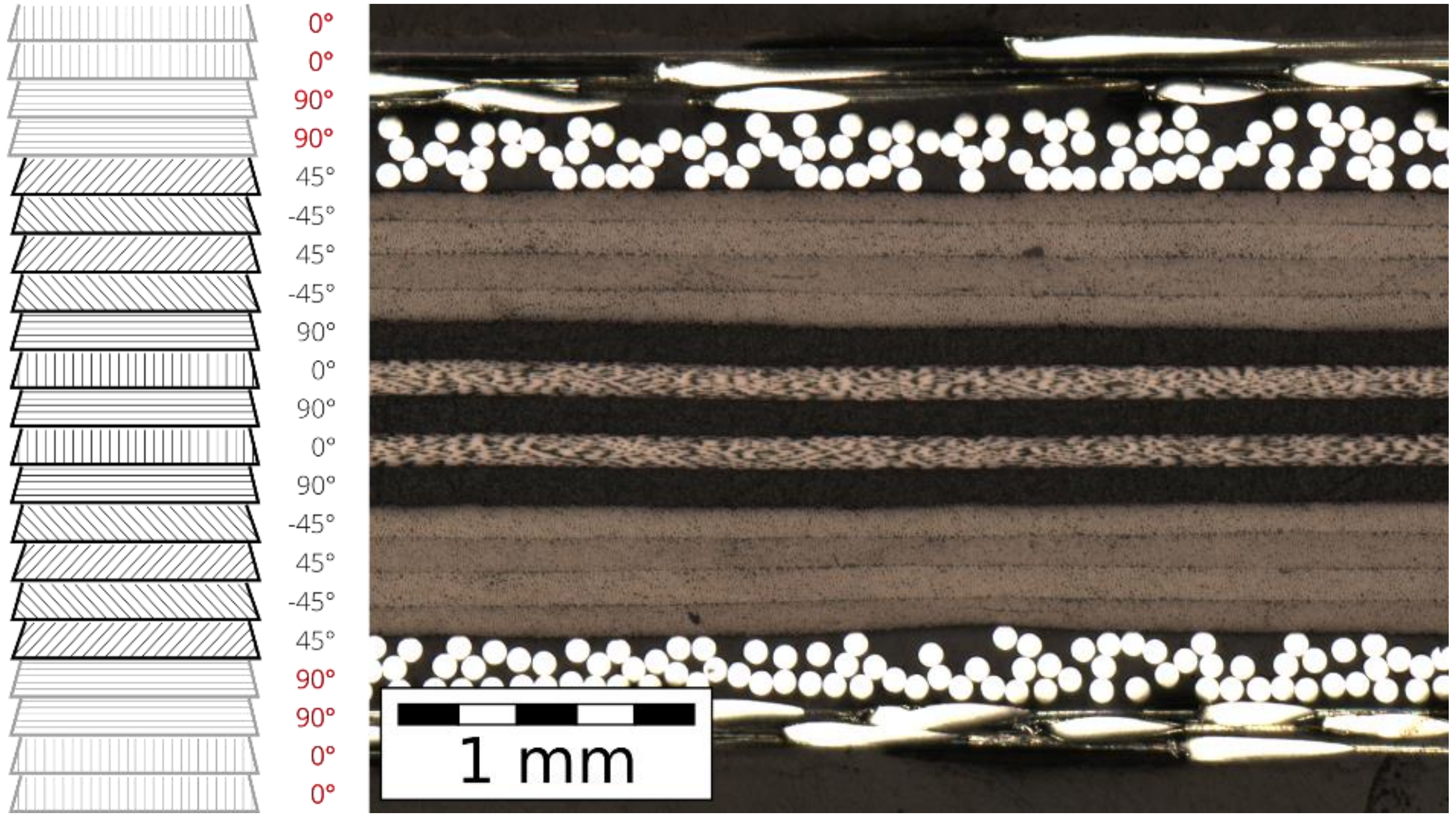


MATERIALS AND METHODS
Laminate Layup

CFRP



MCFRP



Khatri et al., 2022 [2]

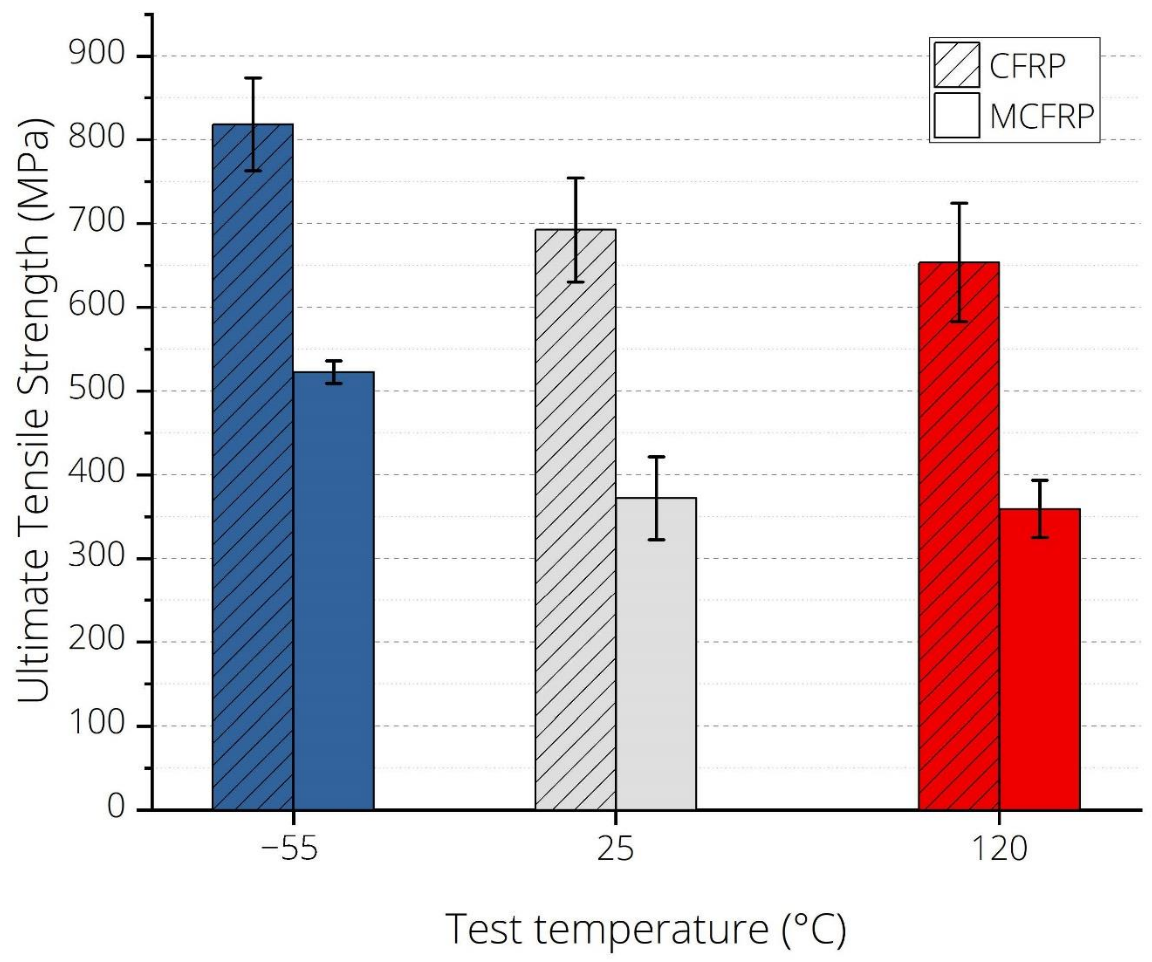
CFRP
- Multidirectional layup with two 0° peripheral layers, forming a total of four 0° CF layers
- 60 vol. % CF in epoxy resin

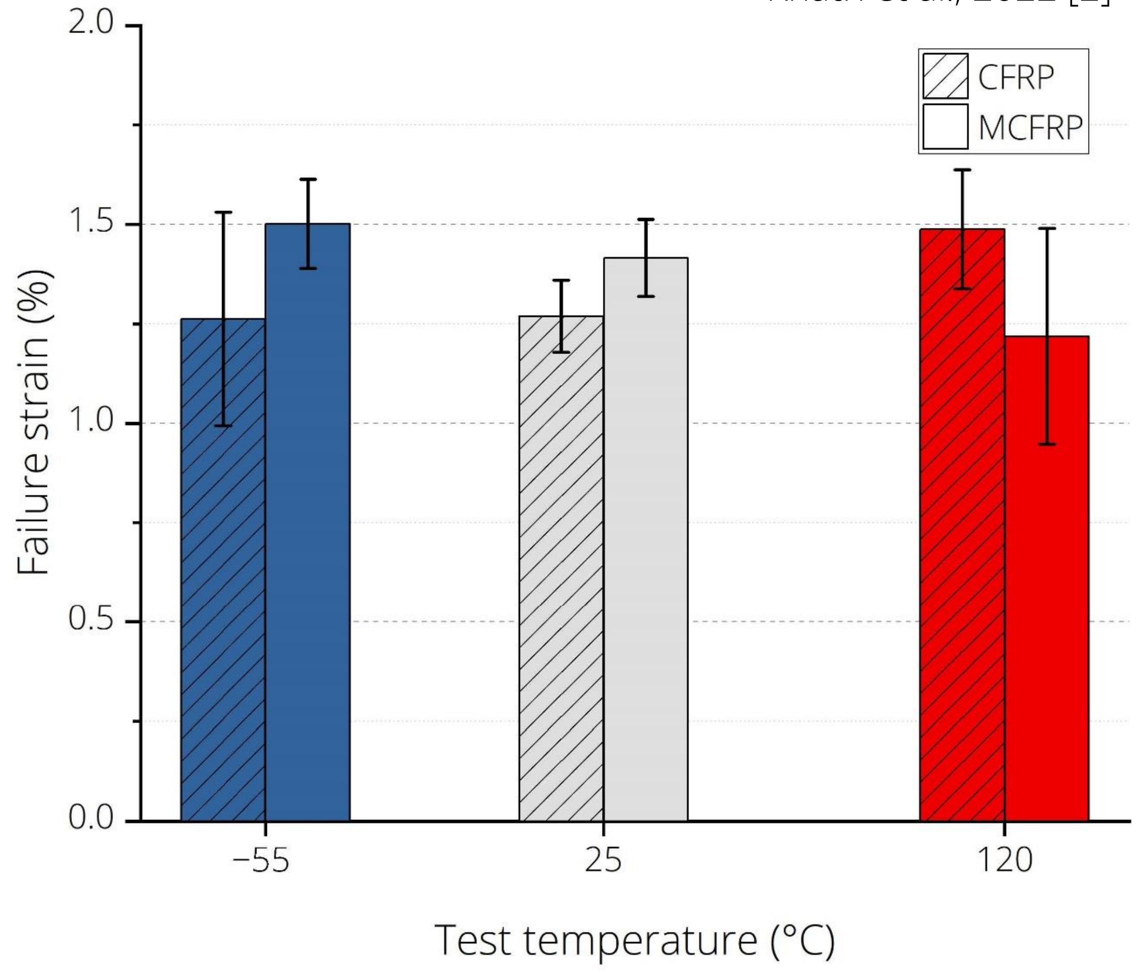
MCFRP
- Eight SF layers replacing the outermost 0° and 90° CF-plies, resulting in two 0° CF-layers and four 0° SF-layers
- CF and SF content: 49 vol. % and 18 vol. % respectively

RESULTS - I

Isothermal tensile tests

Khatri et al., 2022 [2]





- UTS of CFRP higher, due to the two additional 0° plies in its layup
- UTS generally higher at lower temperatures
- Failure strain comparable between CFRP and MCFRP for all temperatures

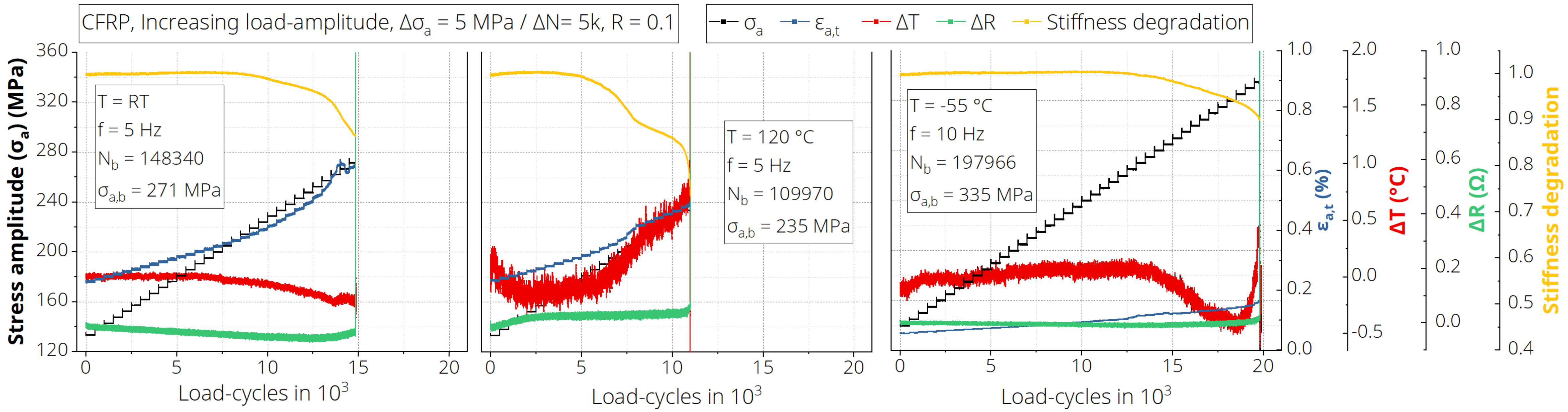
RESULTS - II

Increasing load amplitude tests

- $\Delta\sigma_a$ = 5 MPa every 5×10^3 to 1×10^4 cycles per step (ΔN)

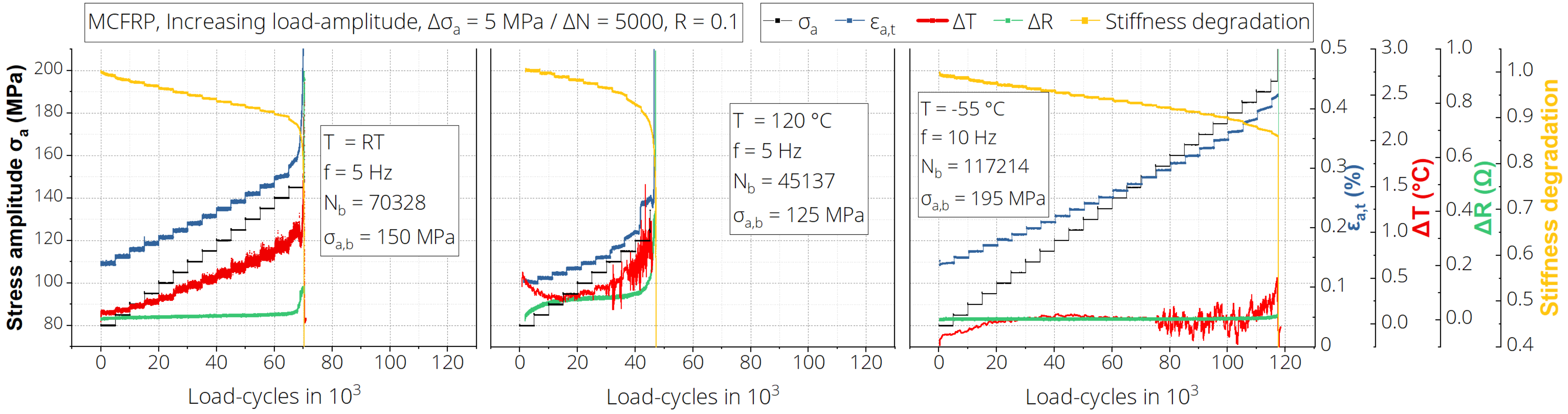
CFRP

- No stiffness degradation until ~50% of N_b
- ΔR constant until failure of 0° CF-layers



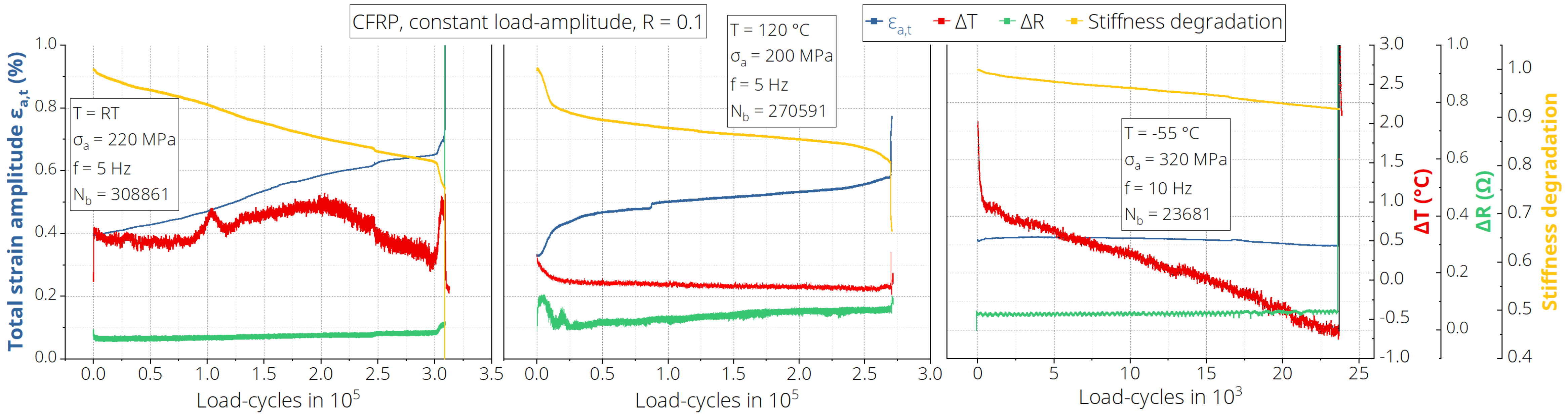
MCFRP

- Stiffness degradation more reactive to the increasing load
- Progressive ΔT at RT
- ΔR dependent on SF breakage

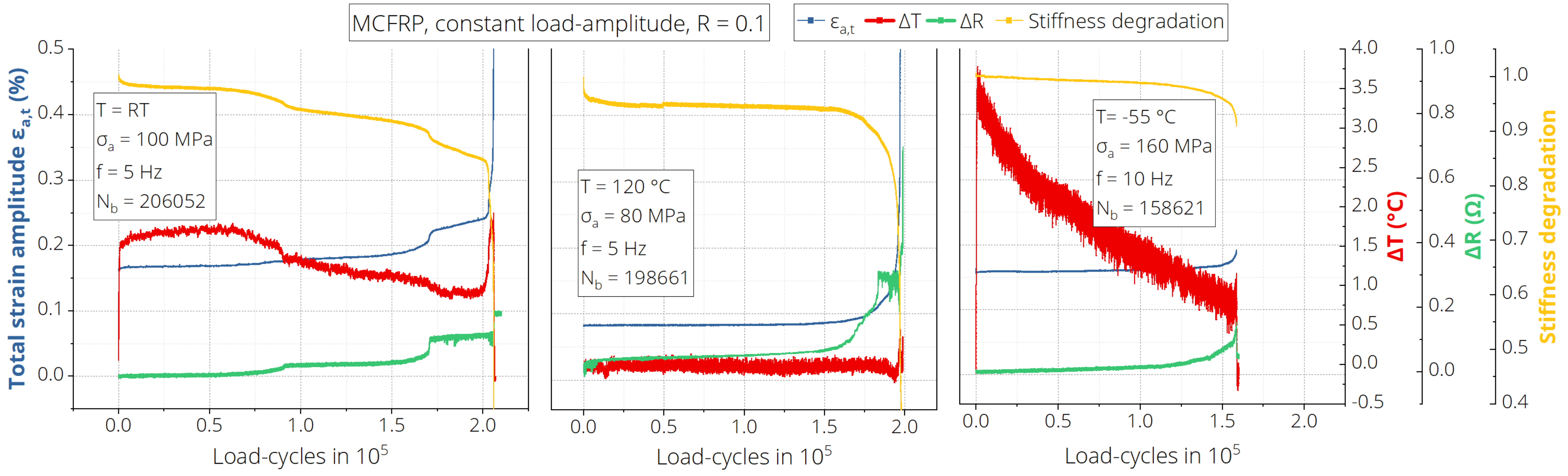


RESULTS - III
Constant load amplitude tests

CFRP
- Fatigue softening and stiffness degradation observed at all three test temperatures
- No significant change in ΔR until failure

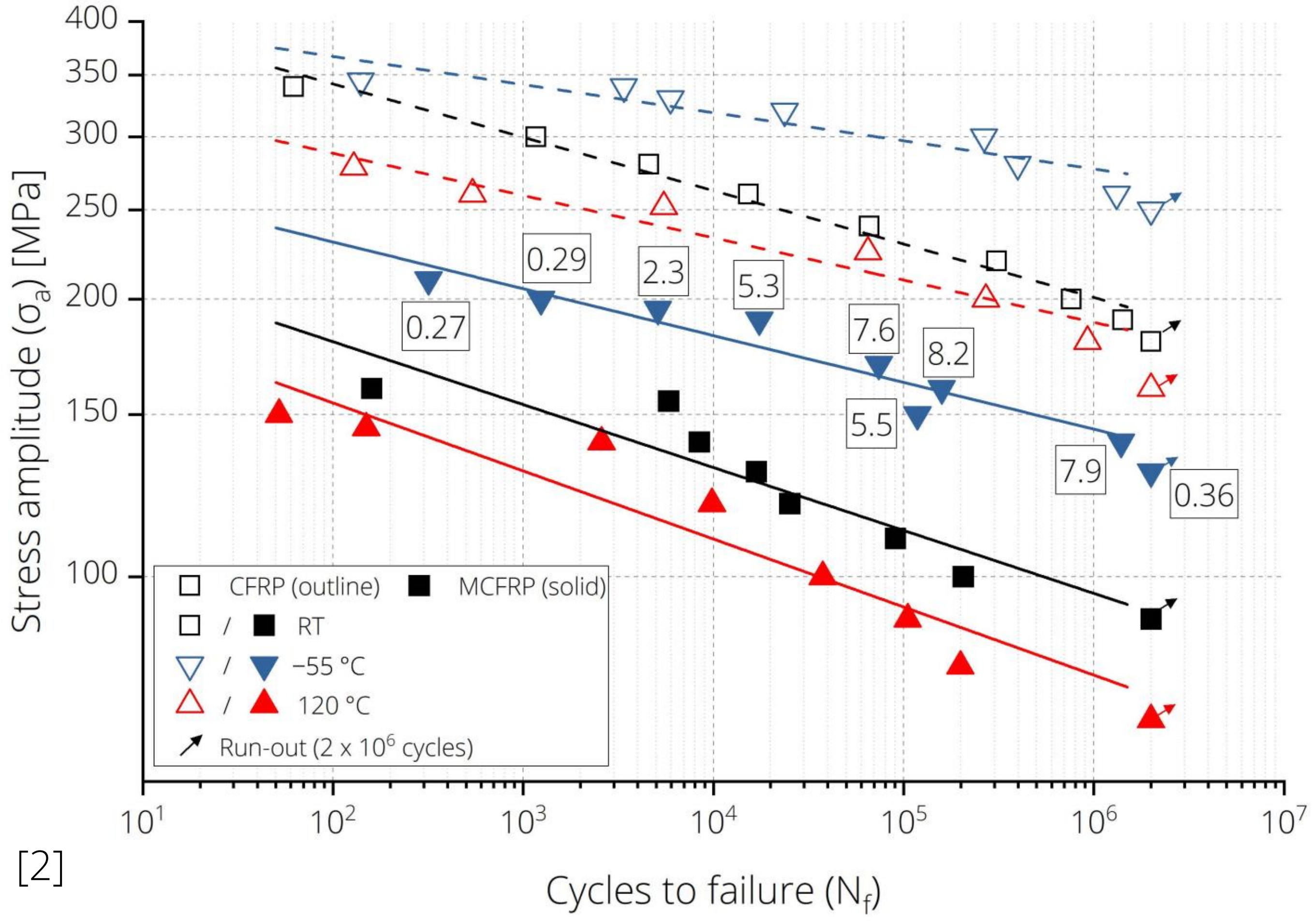


MCFRP
- Initial fatigue softening, followed by a stable stiffness behavior
- Increase in ΔR with SF breakage

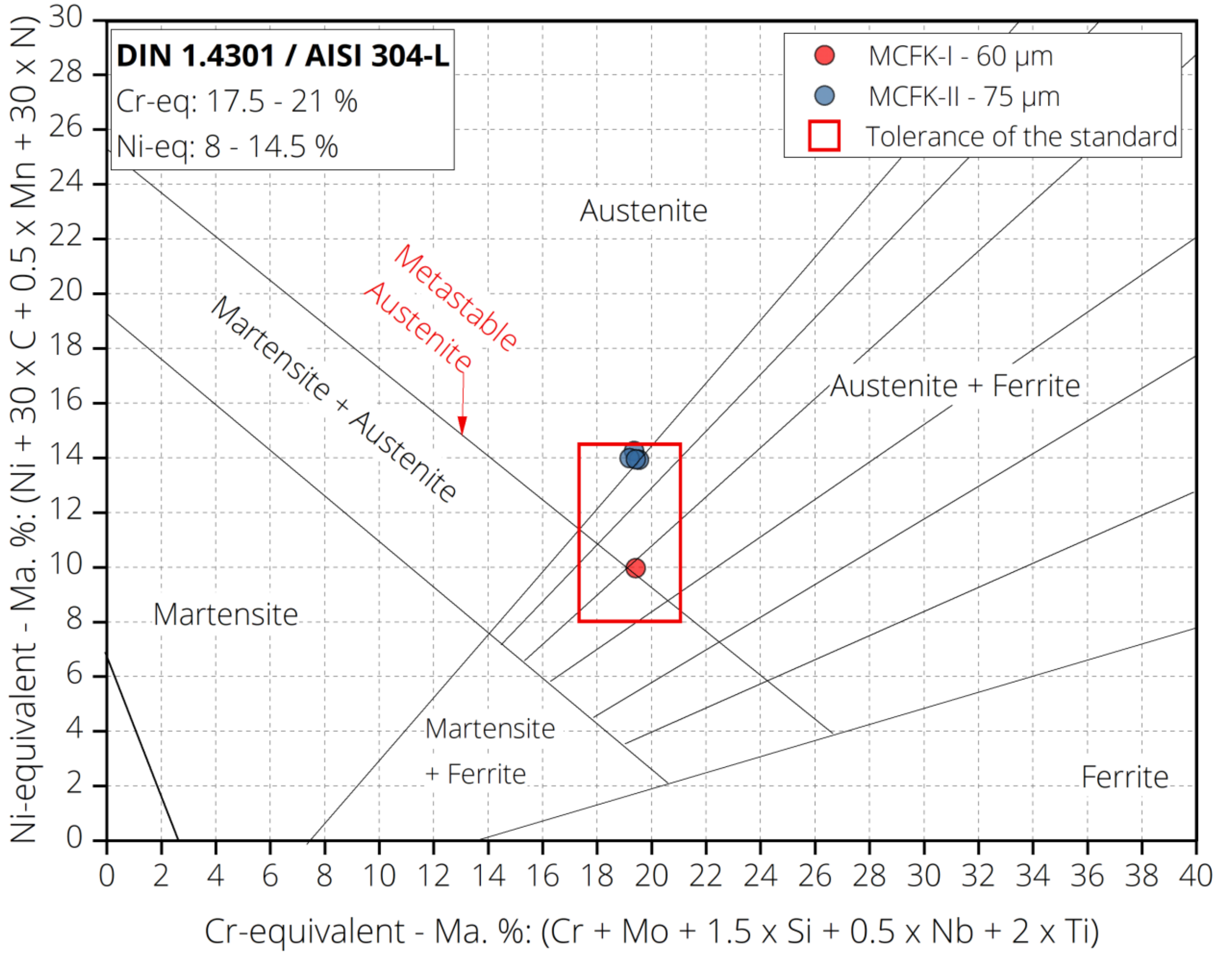


RESULTS - IV

S-N Curves and the martensitic phase transformation



[1, 2]



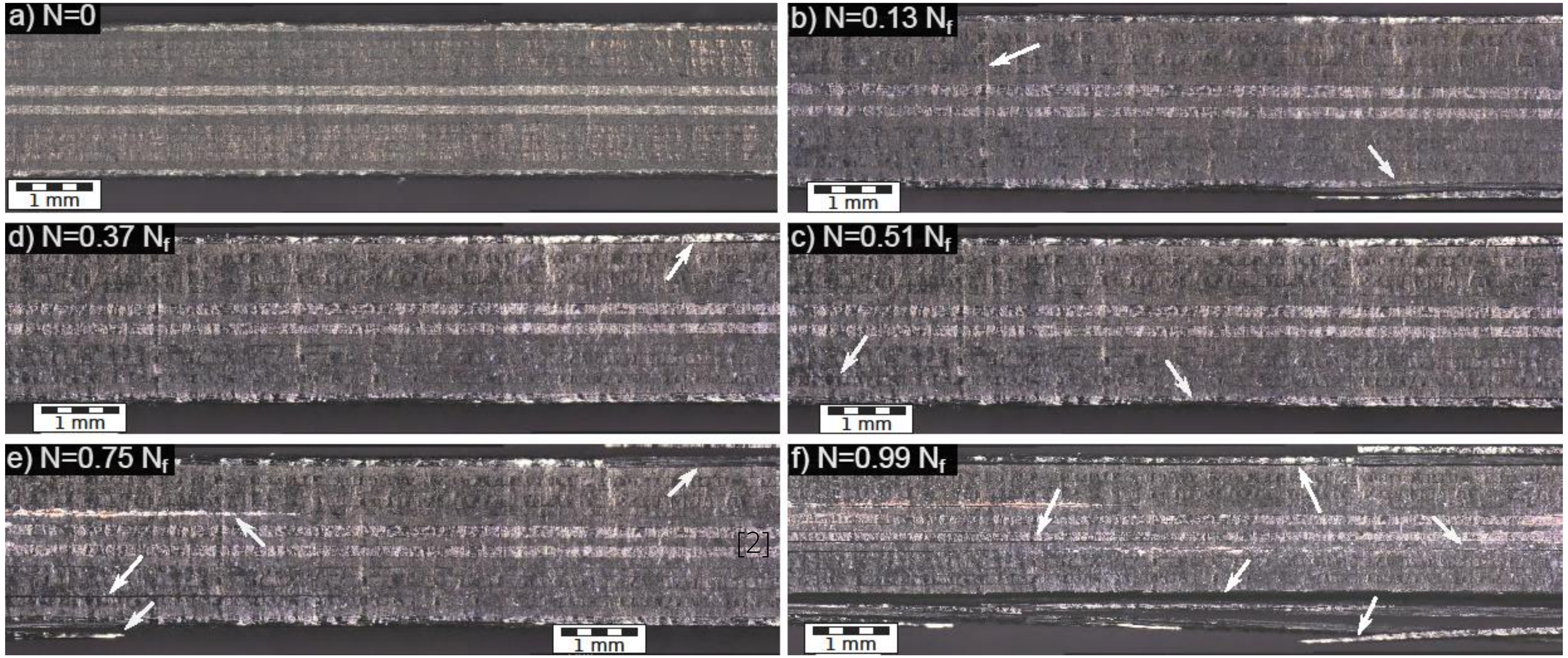
- Both laminates show higher stiffness at lower temperatures
- CFRP is in general stiffer due to the difference in the number of 0°-layers in the laminate
- MCFRP Maximum martensite content of 8.5 % observed, only at -55 °C

- SHM not possible at RT and above due to fiber composition
- Even though the steel fibers lie within the tolerances of the standard, the Ni and Cr equivalent contents measured result in a stable austenite phase at RT
- A more tailored chemical composition of the steel fibers can ensure metastability at RT

RESULTS V

Microscopy and failure behavior - CFRP

Khatri et al., 2022 [2]



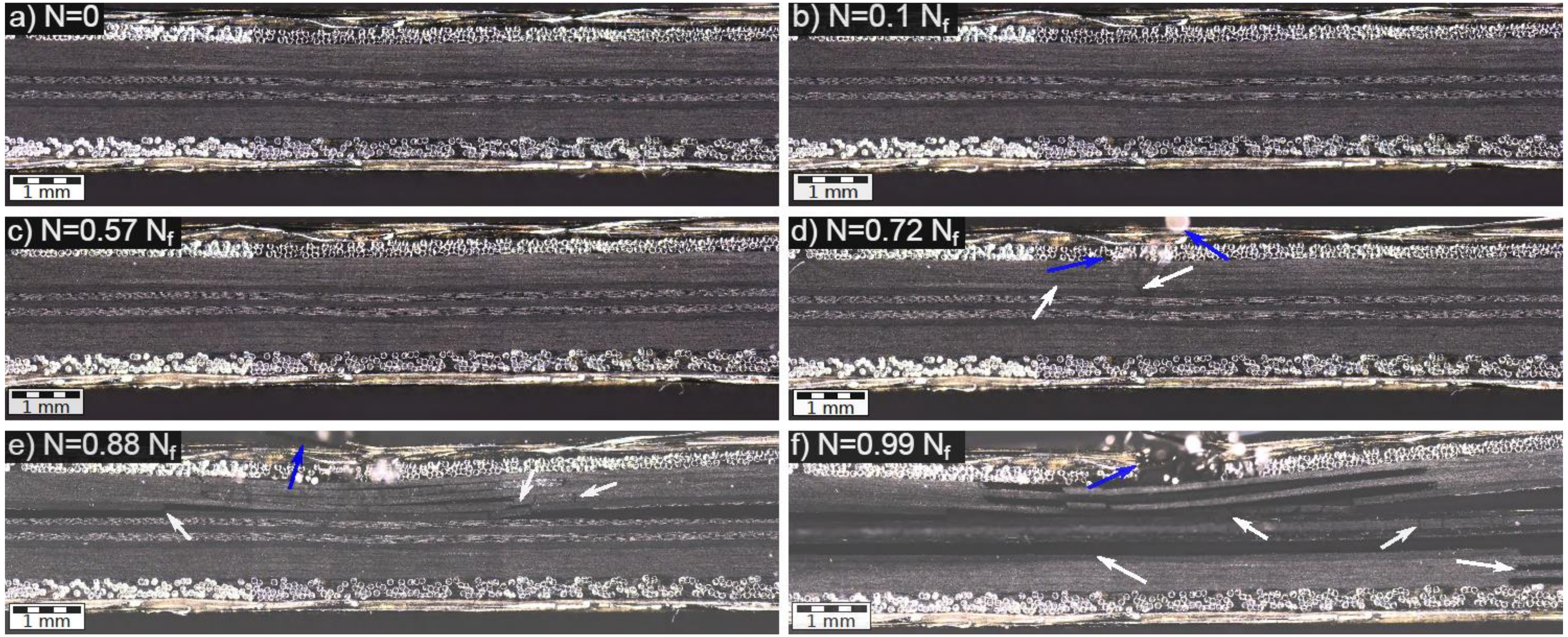
CFRP

- Damage in the outer layers observed as early as 13 % · N_f
- The central 0°-plies intact until after 50 % · N_f
- Delaminations and accelerated damage observed after 75 % · N_f

RESULTS V

Microscopy and failure behavior - MCFRP

Khatri et al., 2022 [2]



[2]

MCFRP

- No significant damage up to ~50 % · N_f
- Steel fiber delamination and breakage precede those of CF
- Accelerated damage of the CF layers observed after 85 % · N_f

Summary

HIGHER STIFFNESS OBSERVED AT LOWER TEMPERATURES

- CFRP up to 30 %, MCFRP up to 40 % stiffer at -55 °C compared to RT

MCFRP SAMPLES EXHIBITED SLOWER FATIGUE ONSET

- Higher plastic deformation observed for MCFRP under fatigue loading
- The inclusion of steel fibers resulted in a more ductile failure behavior

ALLOY COMPOSITION OF STEEL FIBERS CRITICAL

- No martensitic transformation observed at RT
- Up to 8 % martensite measured after CLA tests at -55 °C
- Ni and Cr content in the stainless steel fibers critical, even while remaining within the limits of the DIN 1.4301 standard

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REFERENCES

[1] Backe, S., Balle, F., Hannemann, B., Schmeer, S., Breuer, U.: Fatigue properties of multifunctional metal and carbon-fiber-reinforced polymers and intrinsic capabilities for damage monitoring, *Fatigue Fract Eng Mater Struct.*42:143–151, 2018.

[2] Khatri, B., Rehra, J., Schmeer, S., Breuer, U., Balle, F.: Metal/Carbon-Fiber Hybrid Composites—Damage Evolution and Monitoring of Isothermal Fatigue at Low and Elevated Temperatures. *J. Compos. Sci.*, *6(3)*, 67, 2022.