On the Relation between Crack Densities, Stiffness Degradation, and Surface Temperature Distribution of Tensile Fatigue Loaded Glass-Fibre Non-Crimp-Fabric Reinforced Epoxy

Andreas Gagel, Dirk Lange, and Karl Schulte

Technische Universität Hamburg-Harburg (TUHH), Germany
Polymers and Composites Section (5-09)

http://www.tuhh.de/kvweb

gagel@tuhh.de

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- *Motivation*
    - *Experimental*
        - Quasi-static Tensile Test
        - Fatigue Test
        - Crack Density
        - Mechanical Degradation
        - Thermography
    - *Consideration of Relations*
        - Load / Crack Density
        - Crack Density / Degradation
        - Temperature / Degradation
        - Temperature / Failure
        - Temperature / Crack Density
- *Summary and Conclusion*

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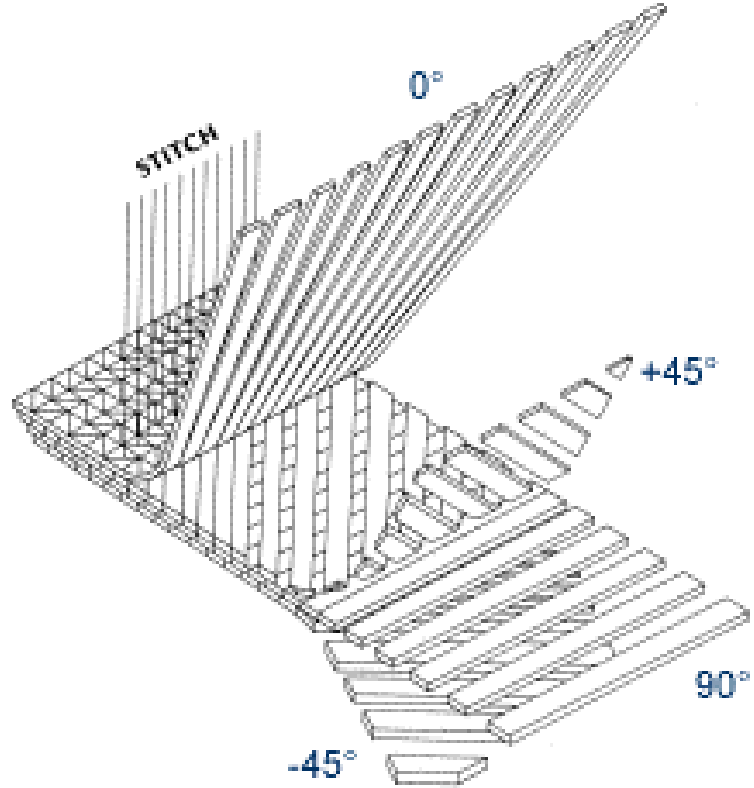
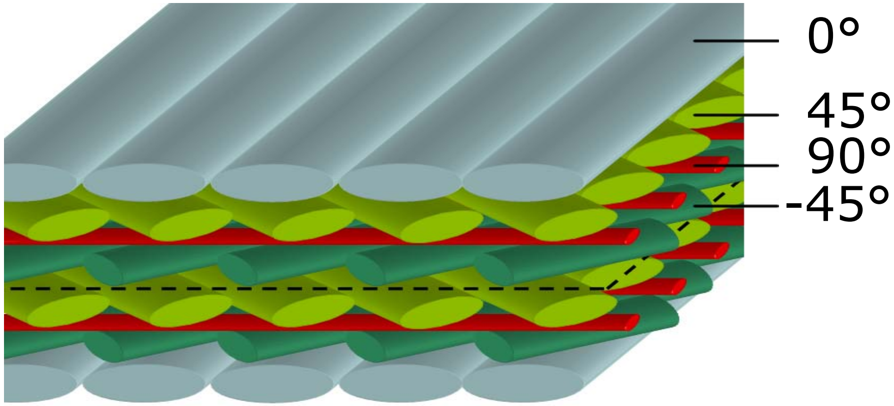


- Large, lightweight, and economical structures with textile reinforced polymers
- High potential of non-crimp-fabric (NCF) reinforced polymers
- Complex damage and failure behaviour
- Understanding the relation between load, damage, degradation and failure

Motivation

Material

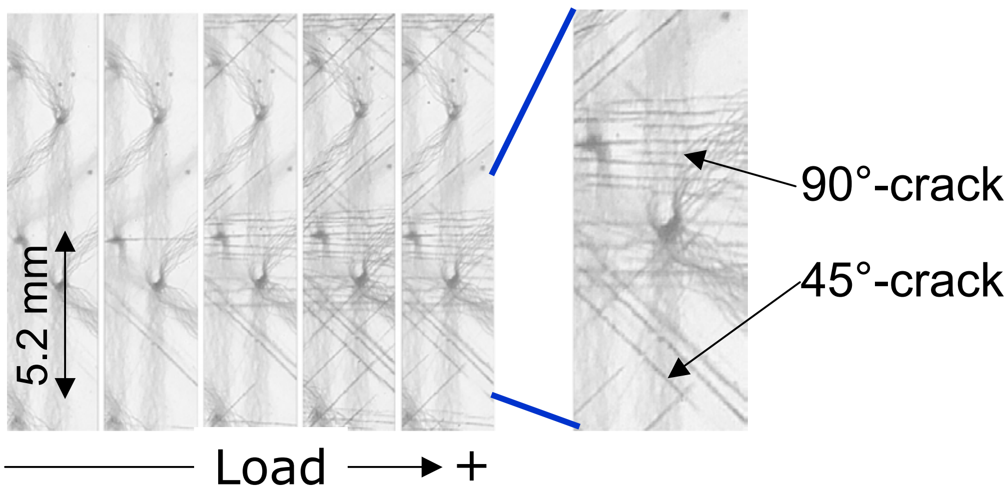


- E-glass fibre non-crimp fabric
- Epoxy L135i/H137 for RTM at RT
- $[0°_{(48\%)}, 45°_{(23\%)}, 90°_{(6\%)}, -45°_{(23\%)}]_{am}$

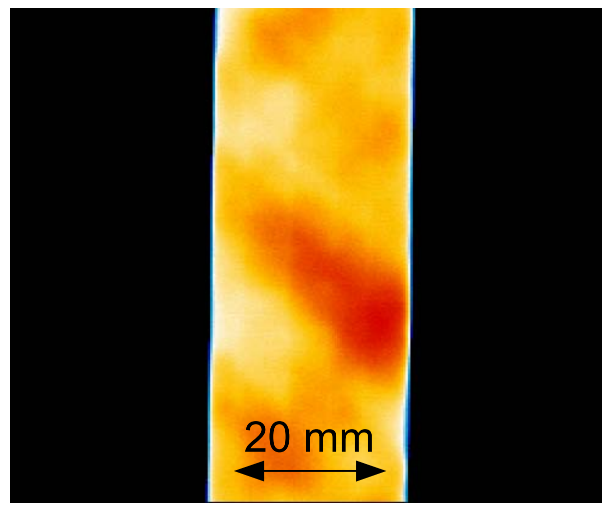
Mechanical Testing

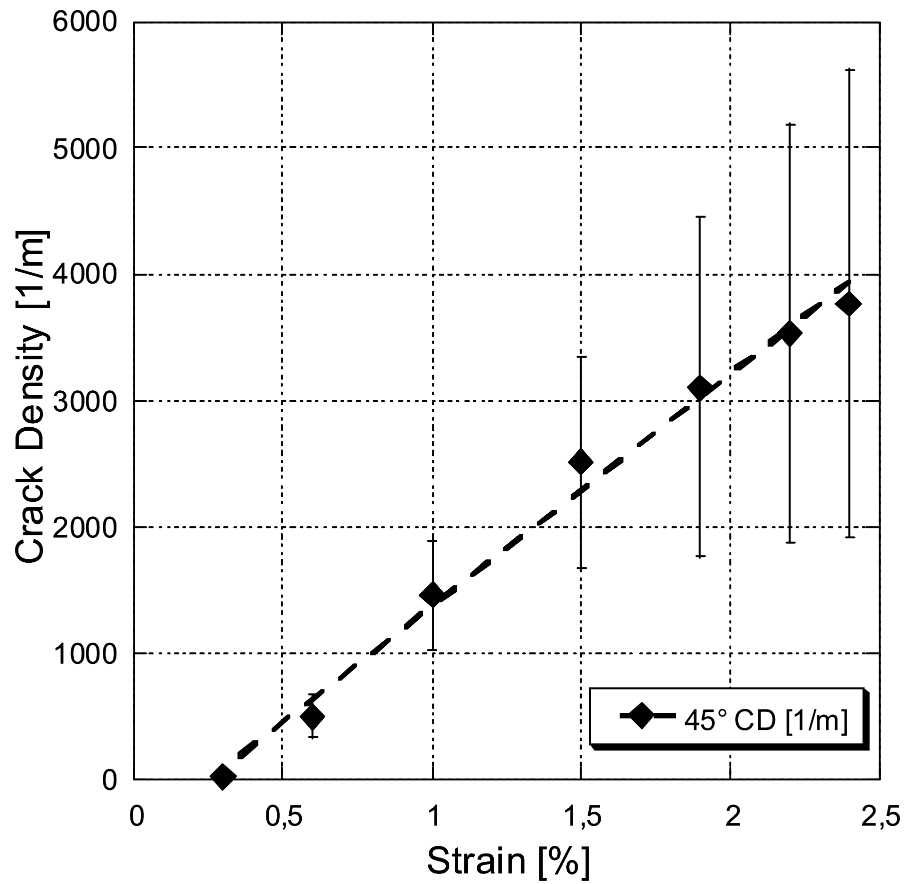
- Specimens DIN EN-ISO 527-4
- Quasi-static tensile test
- Constant amplitude fatigue
- Stress/strain analysis

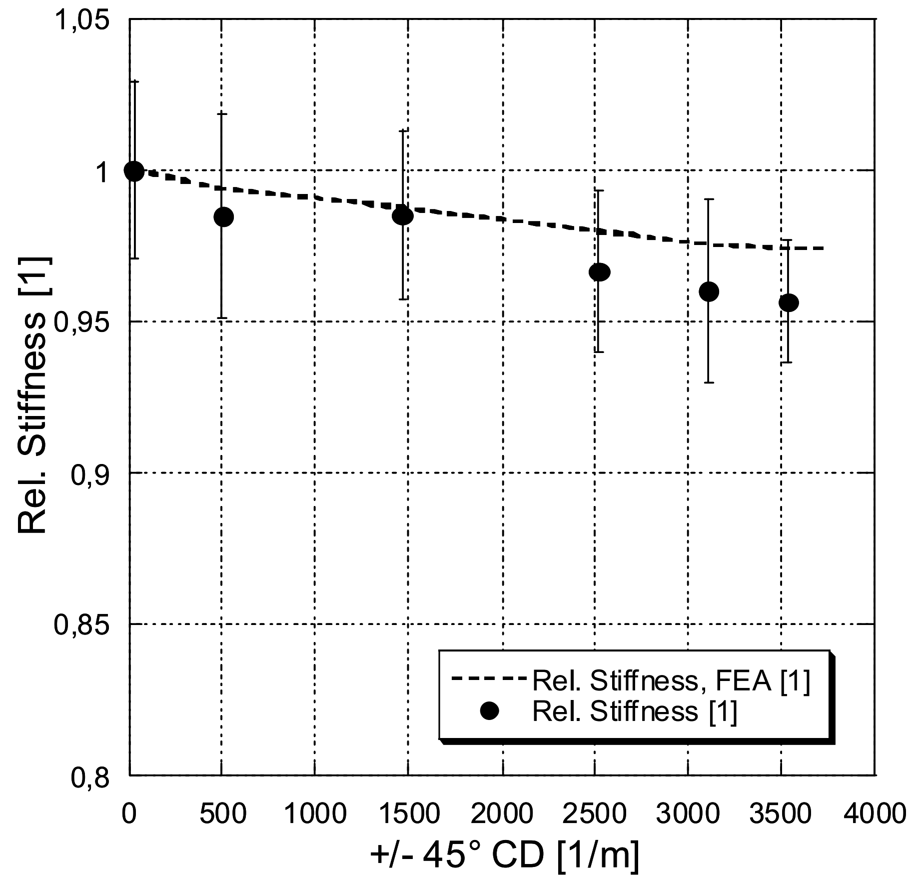
Optical analysis



Thermography





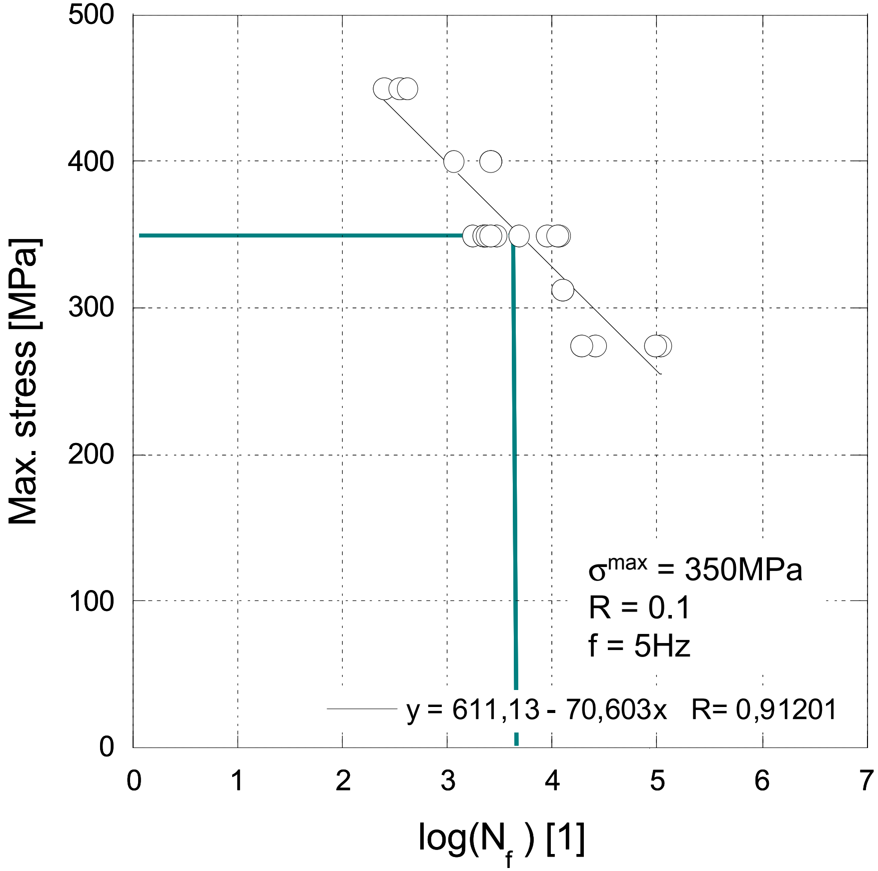


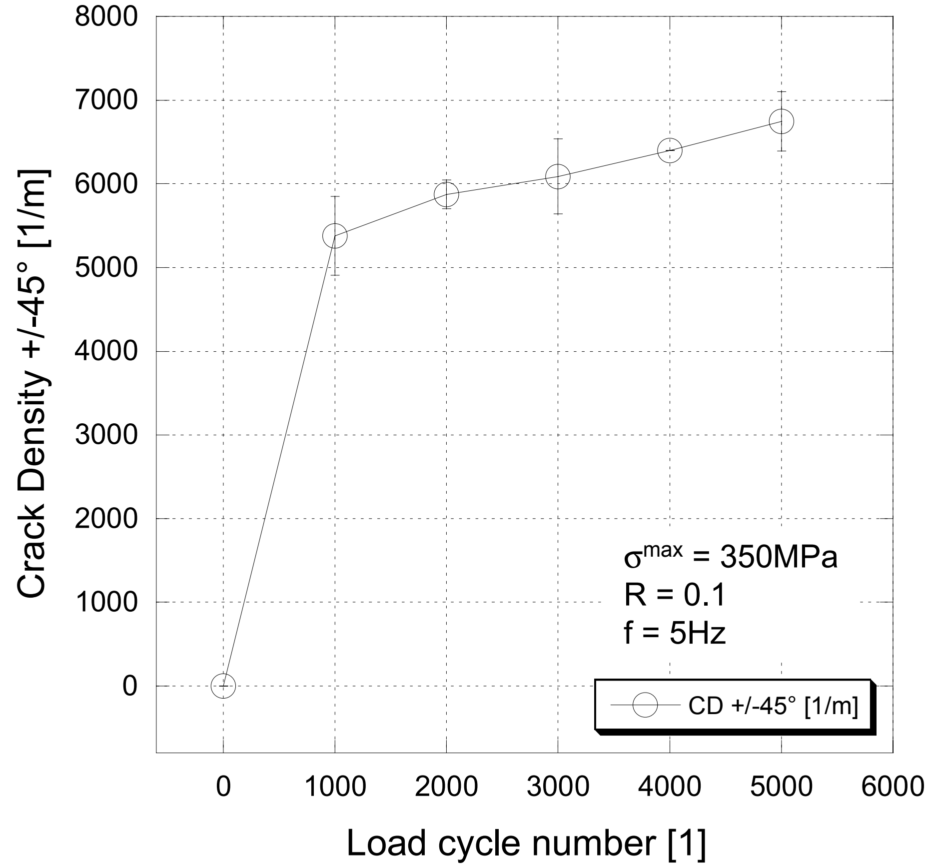
- Quasi-static tensile strain increments
- Optical measurement of crack density
- About linear increase with applied strain
- Onset of cracks between 0.2% and 0.3%

- Development of relative stiffness E/E_0 measured and FEA prediction*
- About linear relation between stiffness and crack density

* A. Gagel, C. Müller, and K. Schulte, ECCM11, Rhode 2004

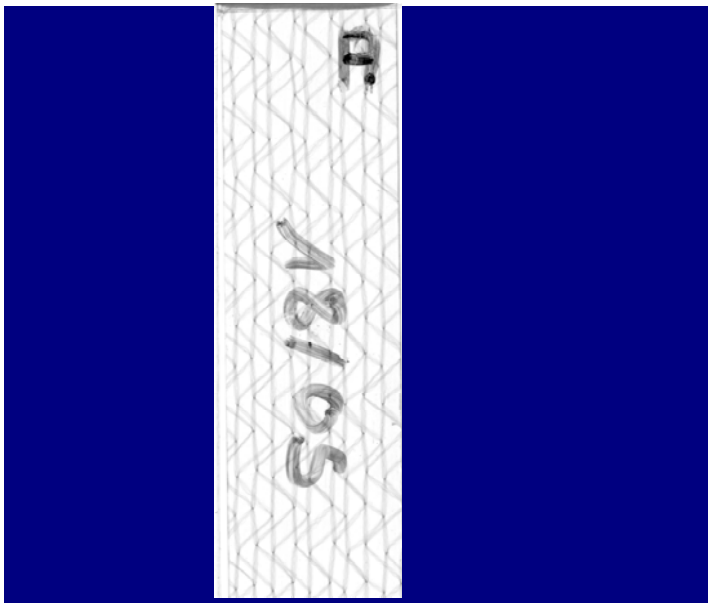
Crack Density and Relative Stiffness
under Quasi-Static Tension

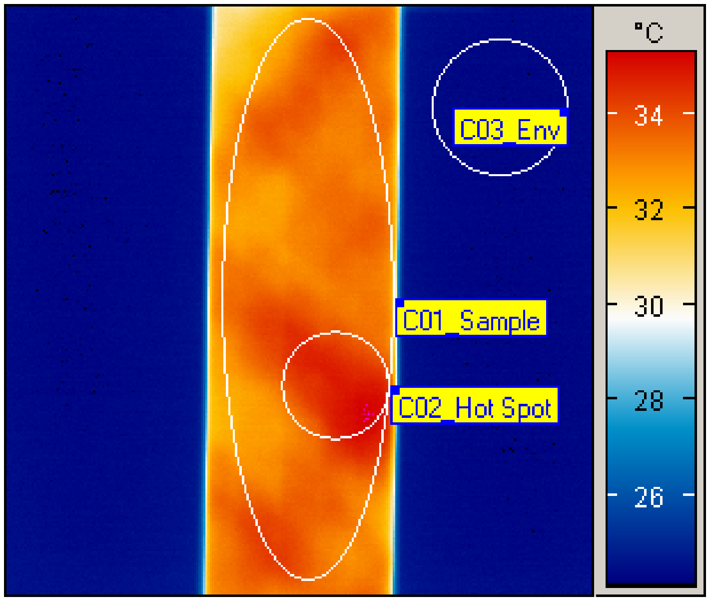




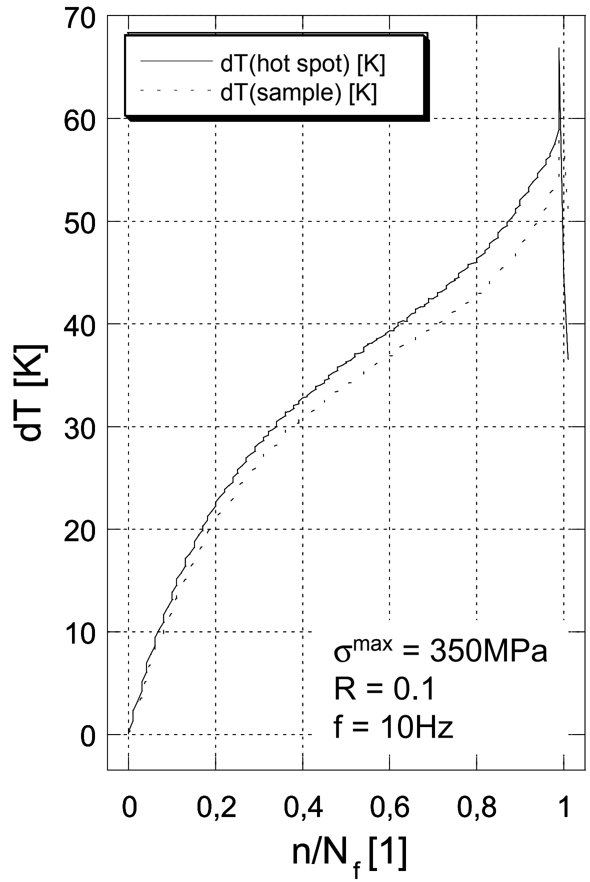
- S-N curve
- Force controlled
- Tension – tension fatigue (R=0.1)
- Test frequency 5 Hz

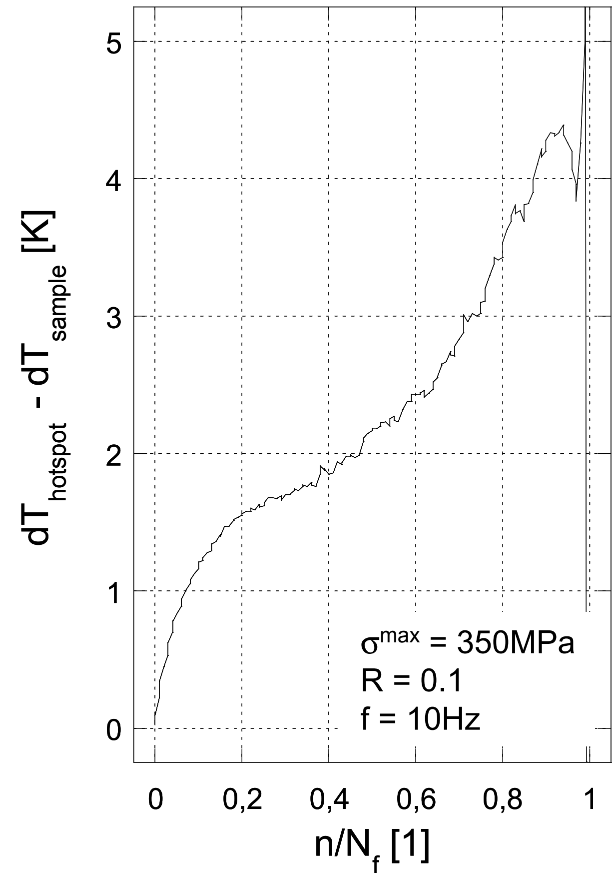
- Interrupted after load increments of 1000 cycles each
- Visual determination of crack density by transmitting light microscopy





f=10Hz, $\sigma^{max}=0.6\ \sigma^{ut}$, R=0.1

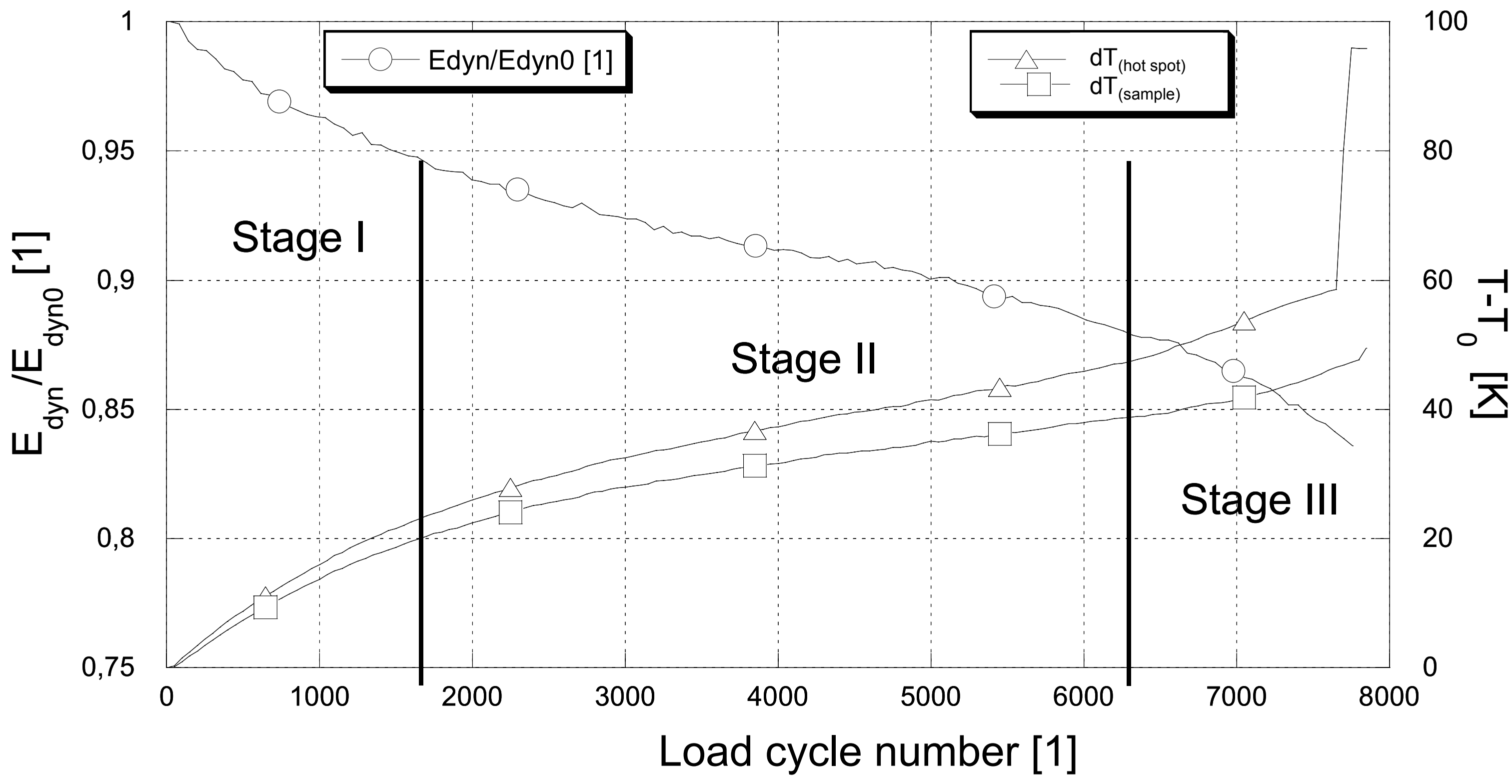




- Heterogeneous distribution while fatigue loaded
- Characteristic zig-zag pattern
- Final failure location early detectable* ($n/N_f<0.1$)

* A. Gagel, B. Fiedler, and K. Schulte, 9th European-Japanese Symposium on Composite Materials, Hamburg, 2004

Surface Temperature Distribution



- Initial, steady and final stage of both stiffness decay and temperature increase
- Mean and hot spot temperature develop proportional until final failure occurs
- Stiffness develops inverse to samples mean temperature

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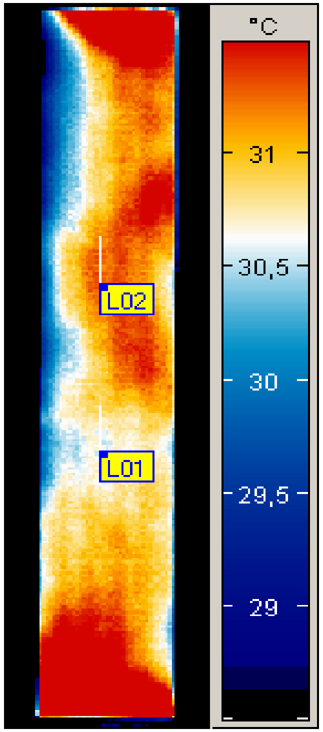
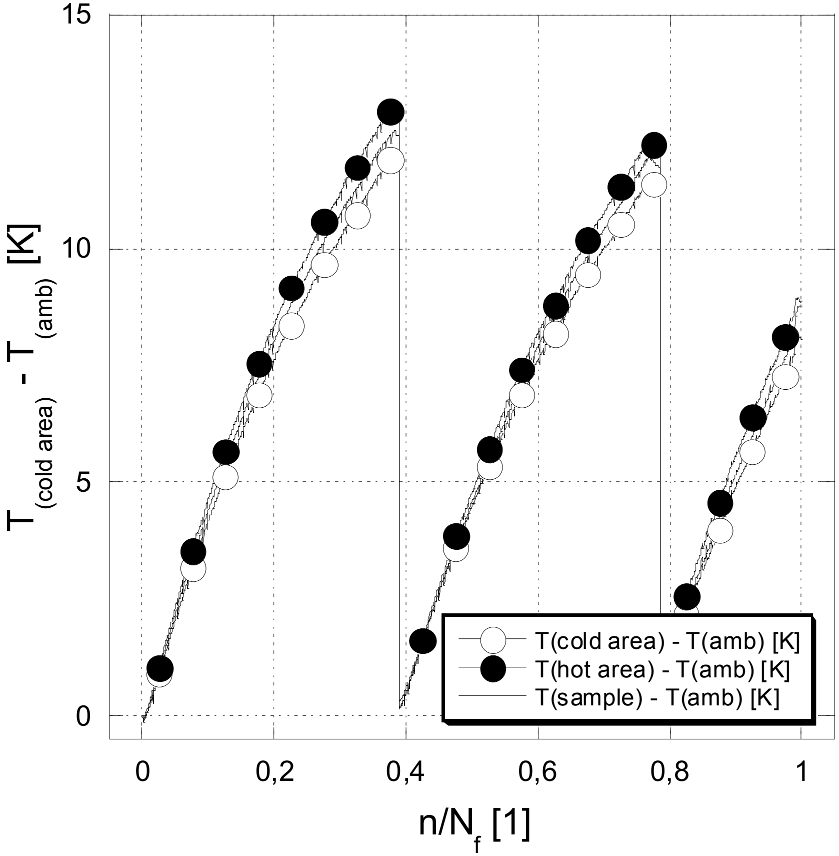
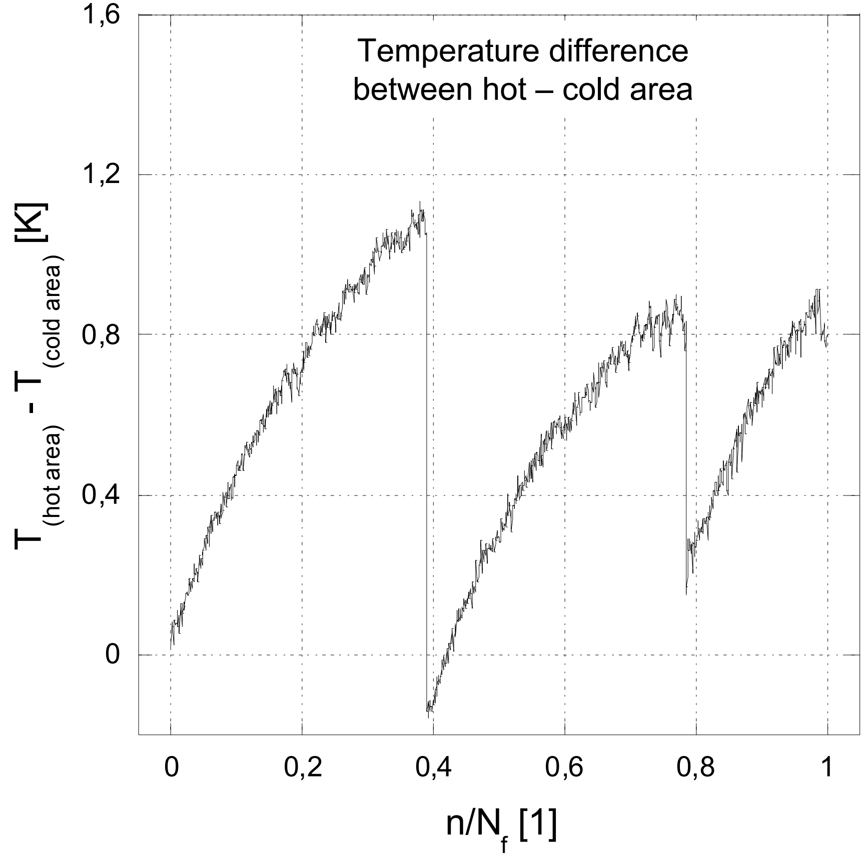
Temperature and Stiffness

Evolution while Fatigue







f = 5Hz,
$\sigma^{max} = 0.6\ \sigma^{ut}$
R = 0.1

- Temperature measurements along sample axis
- Existence of relative (but uncritical) hot (L02) and relative cold (L01) areas
- Temperature distribution does not change significantly with load increments
- Temperature difference about 10% of the samples mean temperature increase

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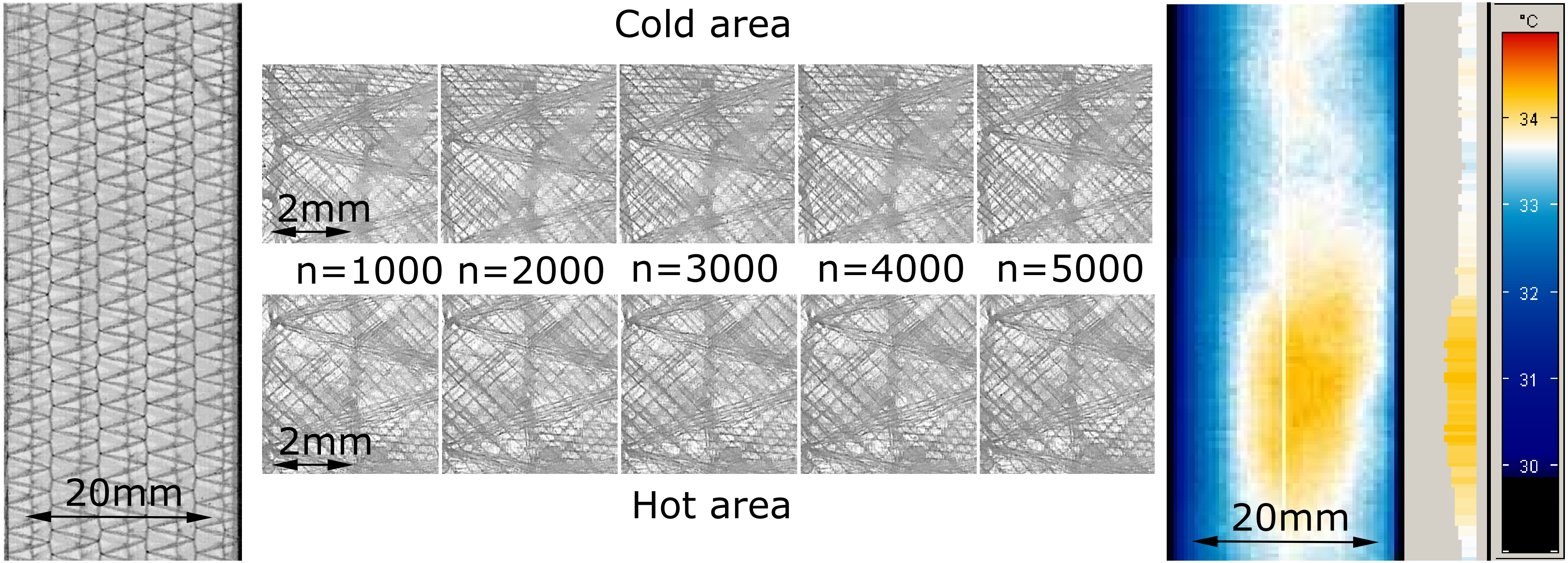
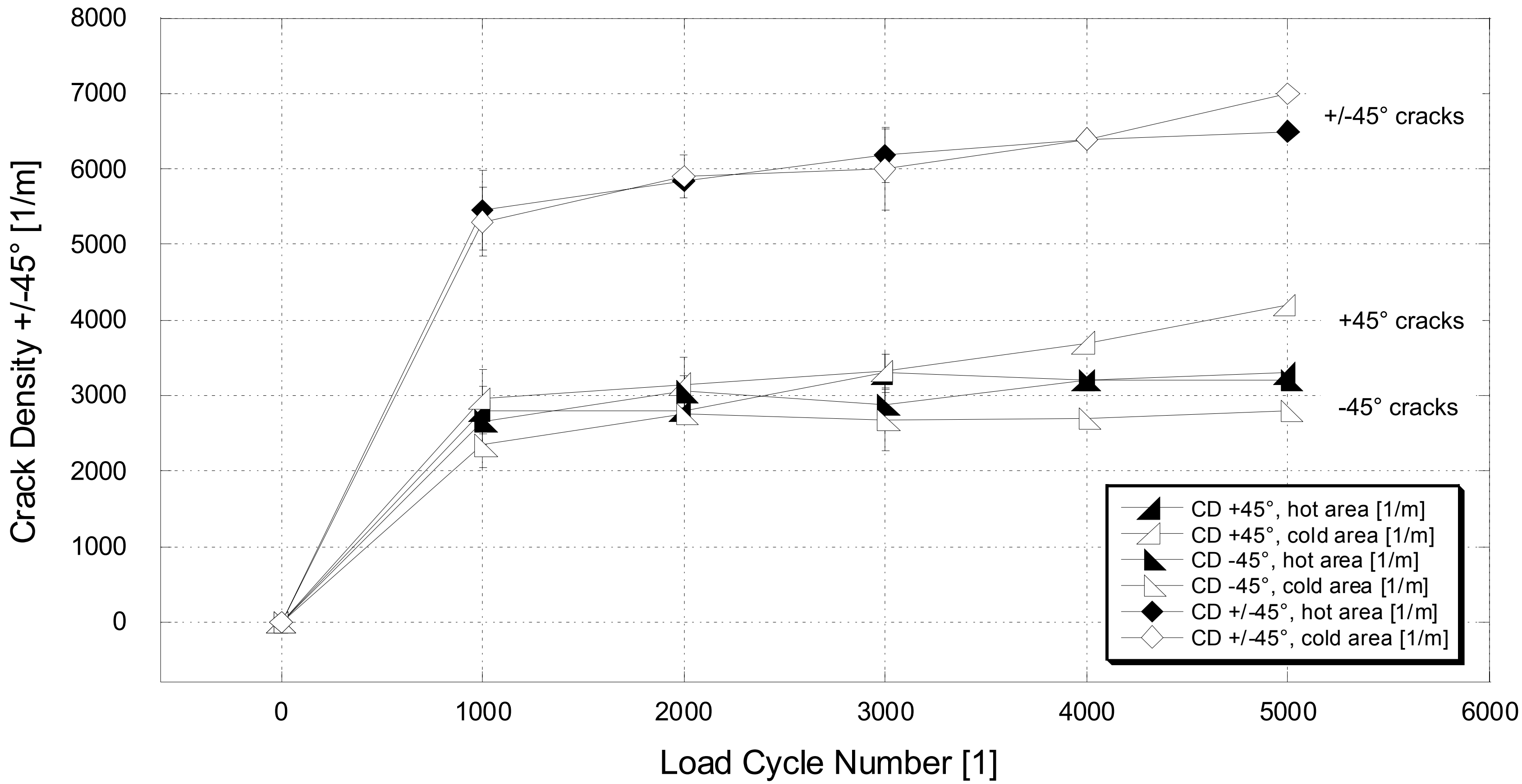
Interrupted Fatigue
Distribution of Surface Temperature



- Defect free sample – no disturbances, voids, etc. visually detectable
- Relative hot and relative cold areas form while fatigue
- No obvious differences detectable with respect to damage types or distribution



- Same crack density measured in hot and cold areas
- Slight, but not significant difference in +45° and –45° crack densities
- Temperature distribution is not caused in local differences of the crack density

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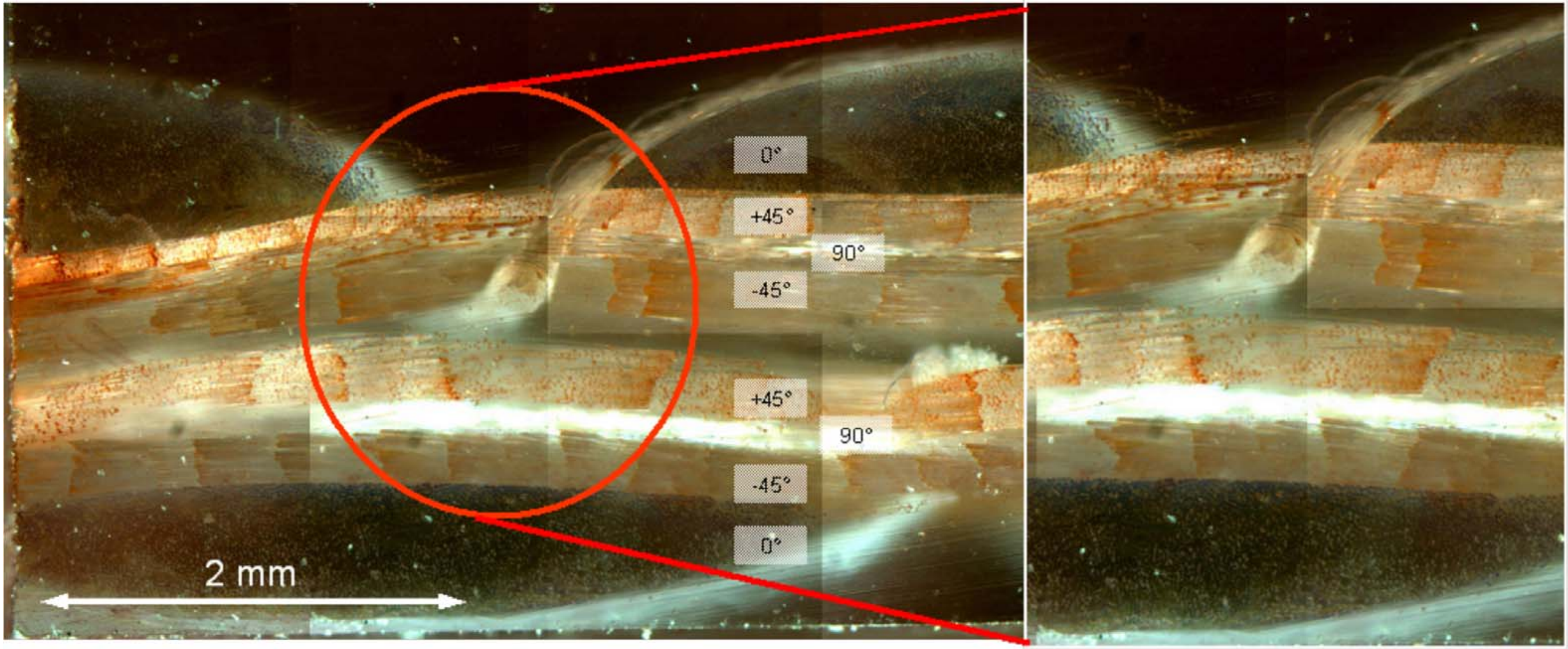
Crack Density in Hot and Cold Areas



Dark field microscopy, staining of inter fibre failures with eosin in alcohol

- Diagonal cracks are evenly distributed in + 45° and -45° degree layers
- In hot and cold areas no differences in crack distribution were found
- Temperature distribution is not caused in spatial crack distribution

Spatial Crack Distribution

Summary

- Onset of inter fibre failure in GF-NCF-EP at low strains between 0.2 and 0.3%
- Three-staged surface temperature increase and stiffness decrease
- Characteristic surface temperature pattern at fatigue load
- Surface temperature and crack density distribution can not be correlated
- The stiffness decrease can be correlated to crack density

Conclusions

1. For GF-NCF-EP under mechanical load the stiffness loss *can be related to and modelled by* the crack density.
2. The location of the fatal failure in fatigue loaded GF-NCF-EP *can be located* via thermography in an very early stage of the fatigue life but
3. The location of the fatal failure *can not be related* to the crack density.

⇒ Stiffness degradation and failure of GF-NCF-EP under fatigue load seem to be governed by different mechanisms.