A continuum damage mechanics model for short fiber reinforced composites

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- Introduction
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- Fatigue degradation model
- Implementation and validation
- Simplified post-processing routine
- Examples
- Conclusions

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Introduction

short fiber reinforced composites

- lightweight materials
- high flexibility regarding design of component shape and complexity
- easy processing using injection molding
- popular materials in many automotive and other transport applications

fatigue under in-service conditions complex process depending on

- fiber volume fraction
- fiber orientation distribution
- local loading situation – triaxial stress state

➢ advanced material model accounting for all relevant effects required for numerical simulation

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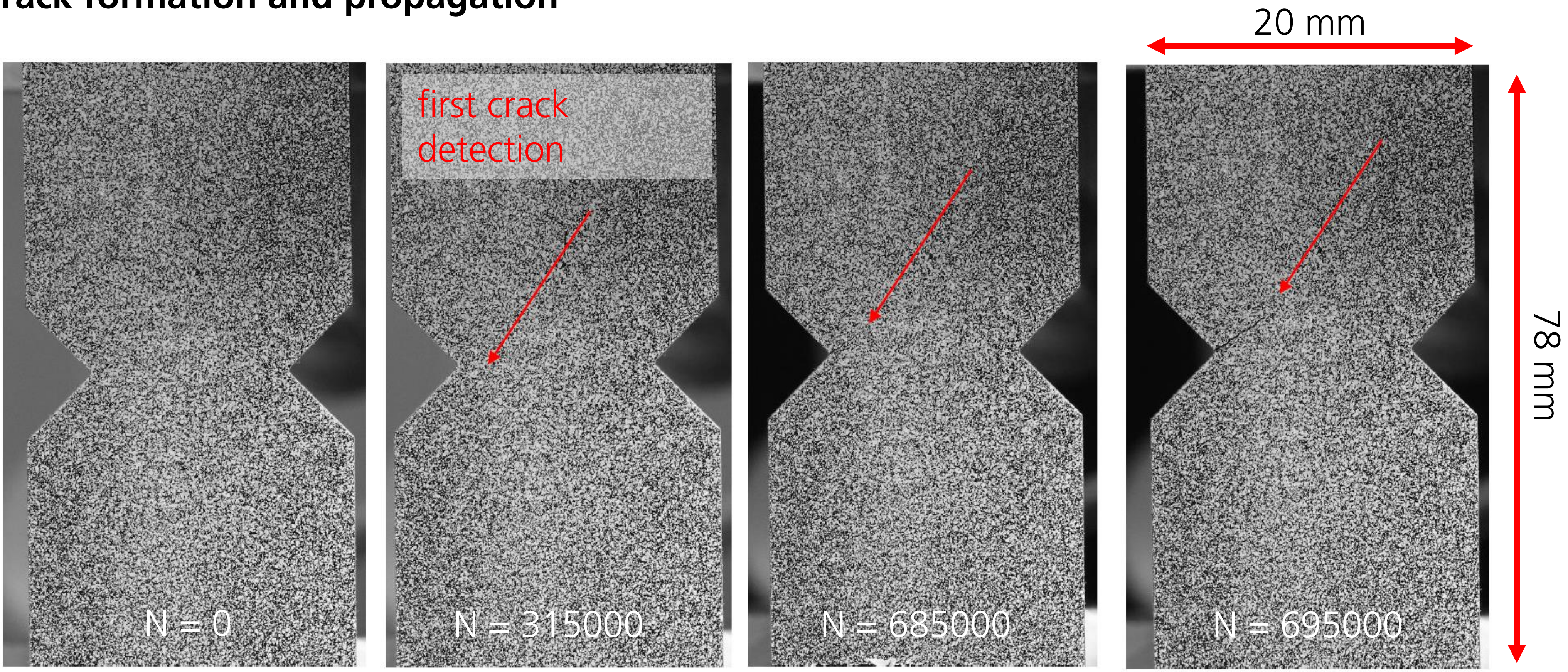
Experimental study

fatigue crack formation and propagation



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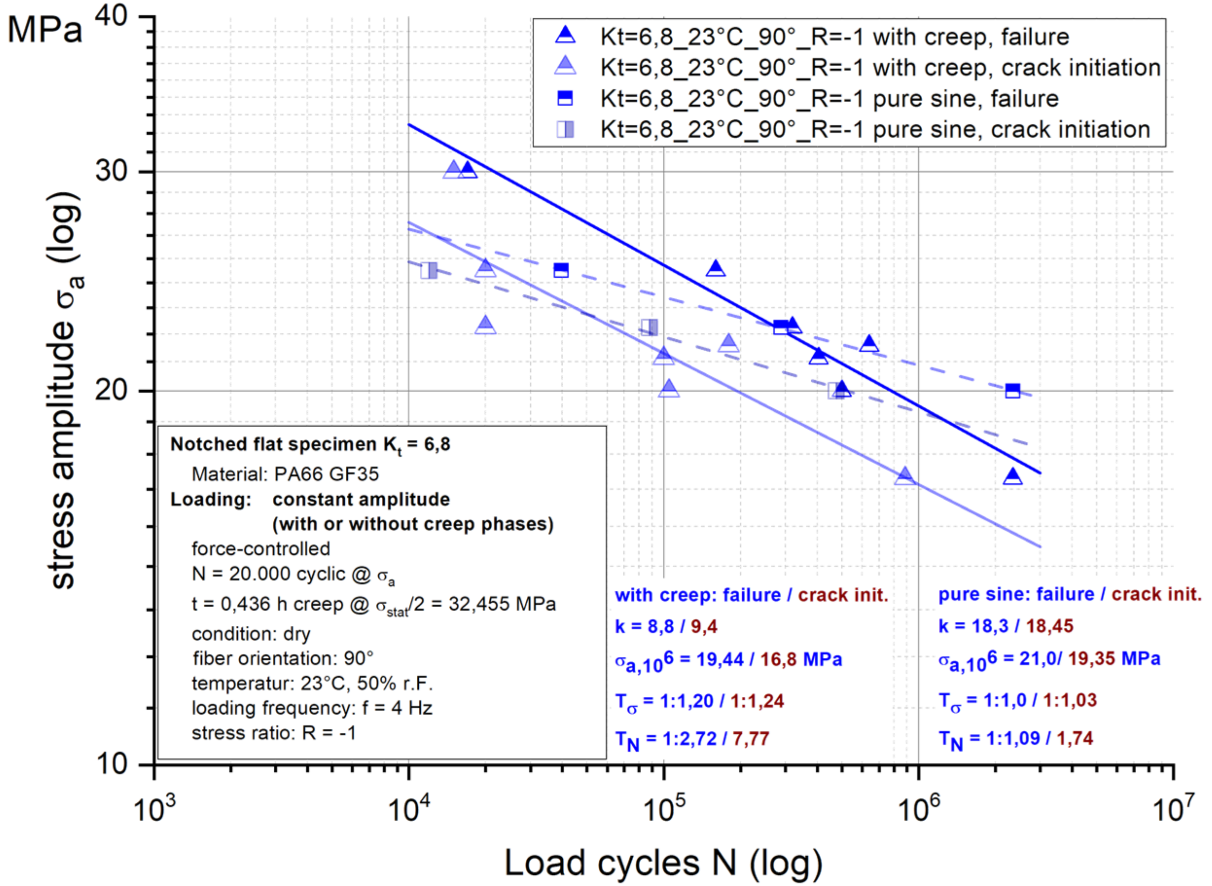
Experimental study

fatigue of notched specimens

- S-N-curves based on crack initiation shifted with respect to S-N-curves based on specimen failure
- creep affects slope of S-N-curves
- investigated further in tests at variable temperature



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Fatigue degradation model

damage variable

- starting point: orthotropic three-dimensional linear elasticity
- introduction of damage

$$\begin{pmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ 2\varepsilon_{23} \\ 2\varepsilon_{13} \\ 2\varepsilon_{12} \end{pmatrix} = \begin{pmatrix} \frac{1}{(1-D)E_1} & -\frac{\nu_{21}}{E_2} & -\frac{\nu_{31}}{E_3} & 0 & 0 & 0 \\ -\frac{\nu_{12}}{E_1} & \frac{1}{(1-D)E_2} & -\frac{\nu_{32}}{E_3} & 0 & 0 & 0 \\ -\frac{\nu_{13}}{E_1} & -\frac{\nu_{23}}{E_2} & \frac{1}{(1-D)E_3} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{(1-D)G_{23}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{(1-D)G_{13}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{(1-D)G_{12}} \end{pmatrix} \begin{pmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{23} \\ \sigma_{13} \\ \sigma_{12} \end{pmatrix}$$

- single damage variable:

$$D = \begin{cases} 0 & \text{initial, undamaged state} \\ 0, \dots, 1 & \text{partially damaged state} \\ 1 & \text{material failure} \end{cases}$$

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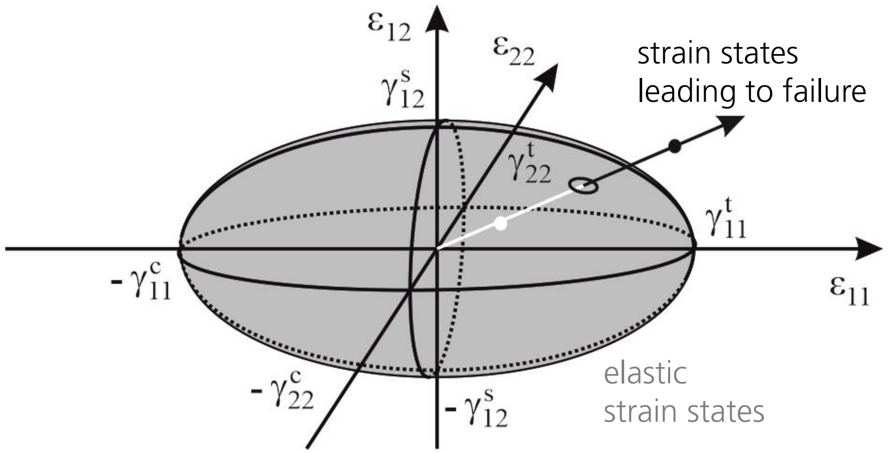
Fatigue degradation model



damage initiation

- failure envelope
  - elastic domain assumed to be bounded by a Tsai-Wu-type failure envelope
  - damage activation function similar to Maimí et al.'s approach: $F = \phi - 1 \leq 0$
  - stress function in 3D-strain space:

$$\phi = \left(\left(\frac{\varepsilon_{11}}{\gamma_{11}^{t}}\right)^{2} - \frac{\varepsilon_{11}\,\varepsilon_{22}}{\gamma_{1122}^{t}} + \left(\frac{\varepsilon_{22}}{\gamma_{22}^{t}}\right)^{2} - \frac{\varepsilon_{22}\,\varepsilon_{33}}{\gamma_{2233}^{t}} + \left(\frac{\varepsilon_{33}}{\gamma_{33}^{t}}\right)^{2} - \frac{\varepsilon_{33}\,\varepsilon_{11}}{\gamma_{1133}^{t}} + \left(\frac{\varepsilon_{23}}{\gamma_{23}^{s}}\right)^{2} + \left(\frac{\varepsilon_{13}}{\gamma_{13}^{s}}\right)^{2} + \left(\frac{\varepsilon_{12}}{\gamma_{12}^{s}}\right)^{2} \right)^{\frac{1}{2}}$$

  - critical strains $\gamma_{ij}, \gamma_{klpq}$: material strength parameters to be determined experimentally
  - static failure once actual strain state reaches failure envelope

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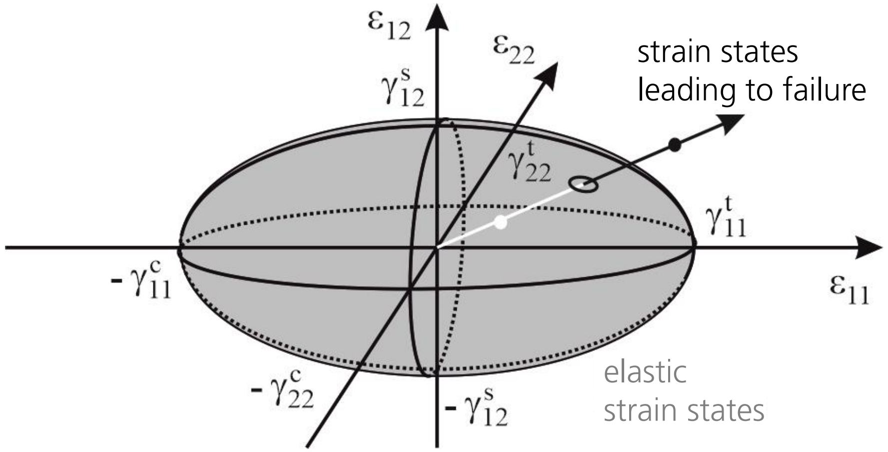
Fatigue degradation model



strain states leading to failure

elastic strain states

damage evolution

- previous 1D stress based model:
  - damage driven by microplastic work: $\mathrm{d}D \sim \mathrm{d}w$
  - microplastic work increment estimated from Ramberg-Osgood equation
  - resulting in: $\mathrm{d}D \begin{cases} \sim \sigma^{n}\,\mathrm{d}\sigma & \text{if } \sigma \geq 0 \\ = 0 & \text{else} \end{cases}$
- assumption here: damage driven by approach of the failure envelope by actual strain state

$$\mathrm{d}D = \begin{cases} A\,\phi^{n}\,\mathrm{d}\phi & \text{if } \mathrm{d}\phi \geq 0 \\ 0 & \text{else} \end{cases} \qquad \text{with } A = 1 + n \qquad \text{due to } \int_{\phi=0}^{1} dD = 1$$

- material parameters: $\gamma^{t}_{11}, \gamma^{t}_{1122}, \gamma^{t}_{22}, \gamma^{t}_{2233}, \gamma^{t}_{33}, \gamma^{t}_{1133}, \gamma^{s}_{23}, \gamma^{s}_{13}, \gamma^{s}_{12}, n$

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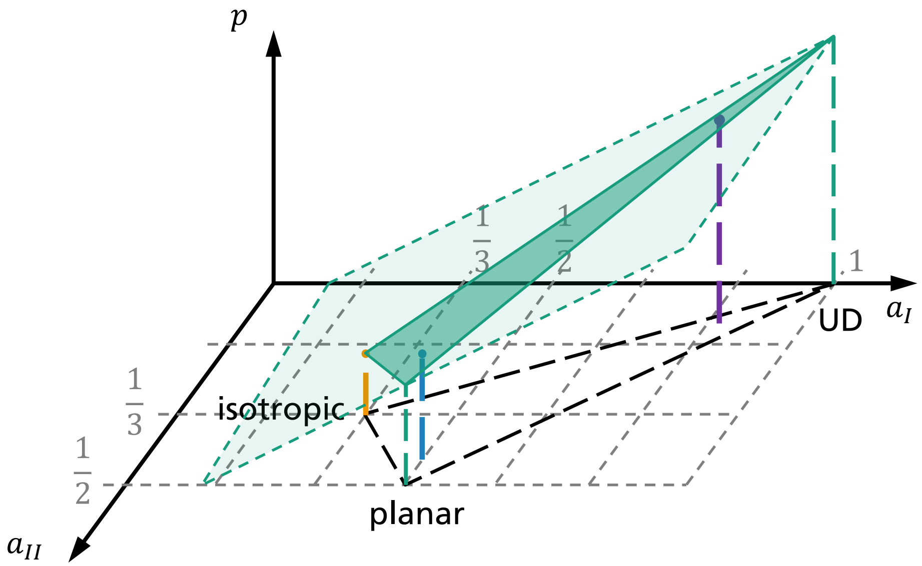
Fatigue degradation model

effect of fiber orientation distribution

- definition of the fiber orientation in terms of the second order fiber orientation tensor

$$a_{ij} = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{12} & a_{22} & a_{23} \\ a_{13} & a_{23} & a_{33} \end{pmatrix} \text{ or alternatively in principal axes space } a_{ij} = \begin{pmatrix} a_I & 0 & 0 \\ 0 & a_{II} & 0 \\ 0 & 0 & a_{III} \end{pmatrix}$$

- determination of the parameters in the principal axes system at three reference states
- interpolation in between the orientation states
- for variable temperature interpolation between selected discrete “thermal nodes”



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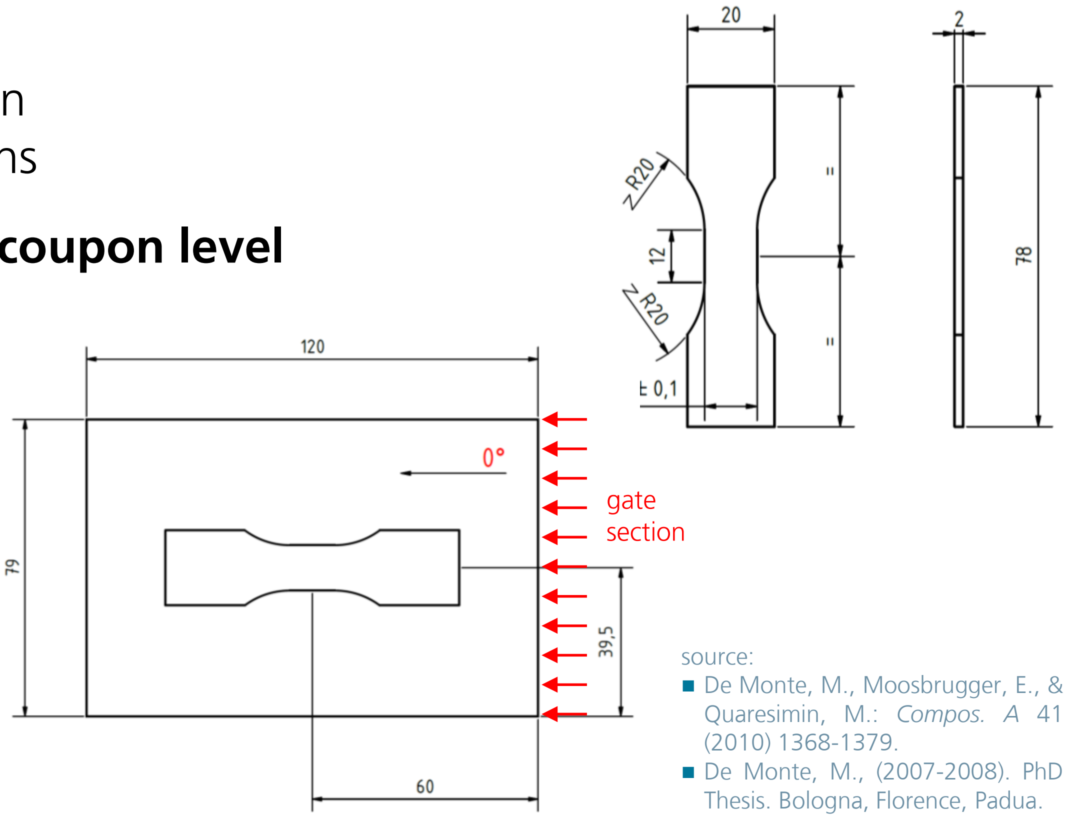
Implementation and validation

implementation as a user defined model into commercial finite element program (ABAQUS)

- time domain formulation
- numerically efficient formulation since strain space formulation avoids (iterative) solution of local nonlinear system of equations

preliminary validation against experimental data base at coupon level

- material PA66 GF35
- tension-tension fatigue (R=0.1) at 10 Hz
- specimen orientation: 0°, 30°, 90°
- ambient temperature (23°C)
- dry as molded condition (rel. humidity < 0.1 wt%)



source:
- De Monte, M., Moosbrugger, E., & Quaresimin, M.: *Compos. A* 41 (2010) 1368-1379.
- De Monte, M., (2007-2008). PhD Thesis. Bologna, Florence, Padua.

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Simplified post-processing routine

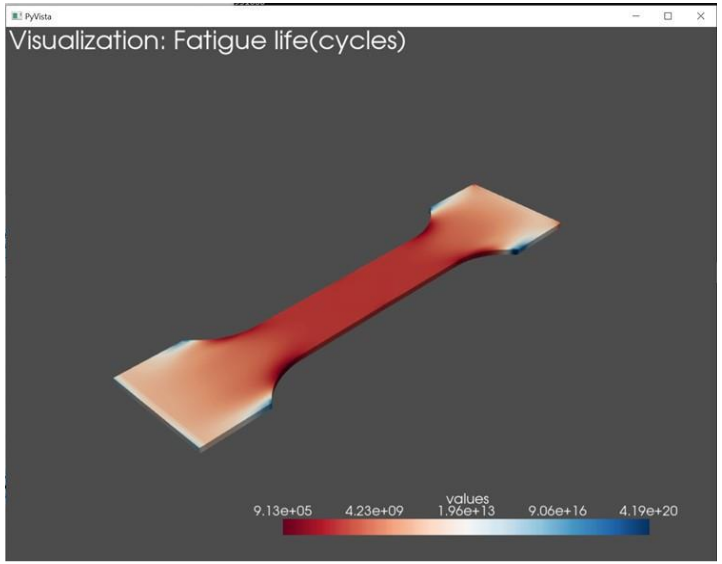
post-processing version of the model implemented in Python 3:

- neglects creep → linear model → unit-load FEA and scaling of strain results

$$\varepsilon_{ij,ref} = f\left(L_{ref}\right) \qquad \varepsilon_{ij}(t) = \frac{L(t)}{L_{ref}}\varepsilon_{ij,ref} \qquad i,j \in \{1,2,3\}$$

- numerical integration of damage evolution for nodal strain-time function

$$D = \int \frac{dD}{dt}dt = \int A\Phi^n \frac{d\Phi}{dt}dt \qquad for\ d\Phi > 0$$



contour plot of nodal fatigue lives (example)
source: final report IGF-project no. 20474 N

with A, Φ, n defined as above.

➢ lower computational expenses but simplification reduces accuracy

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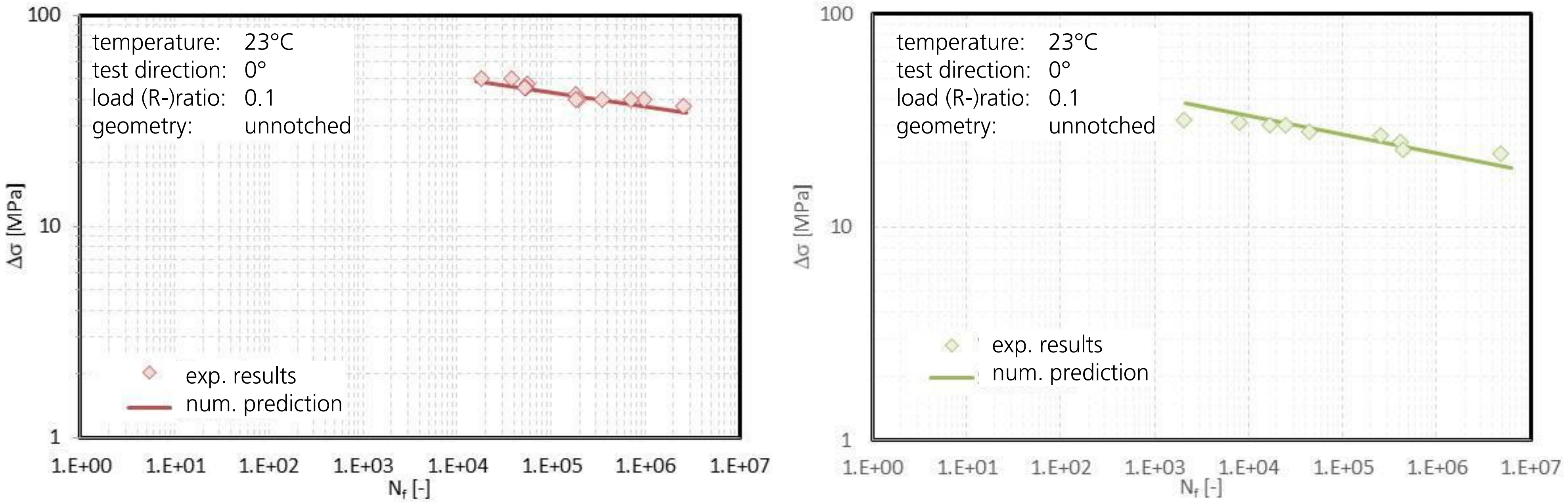
Examples

preliminary validation against experimental data base at coupon level

- results



- ➢ good approximation of experimental results by proposed fatigue damage model
- ➢ perfect prediction of S-N-curve as straight line in double logarithmic representation

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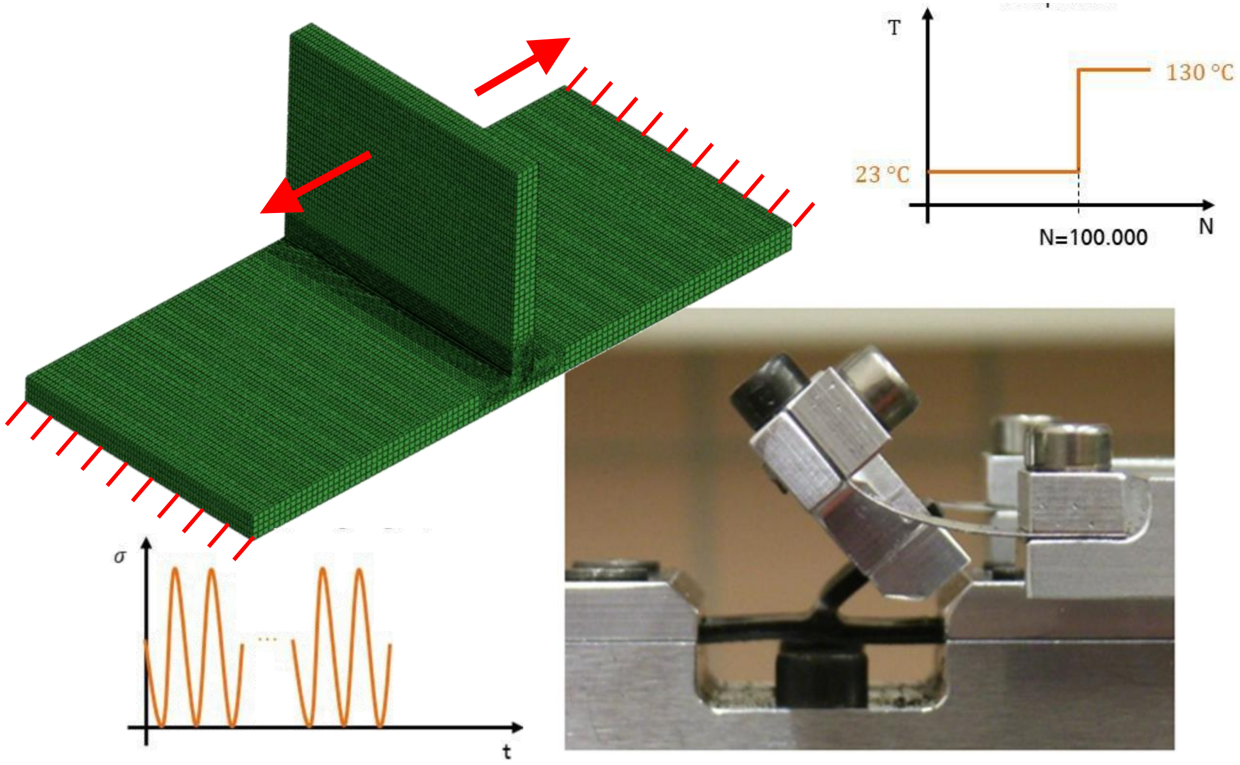
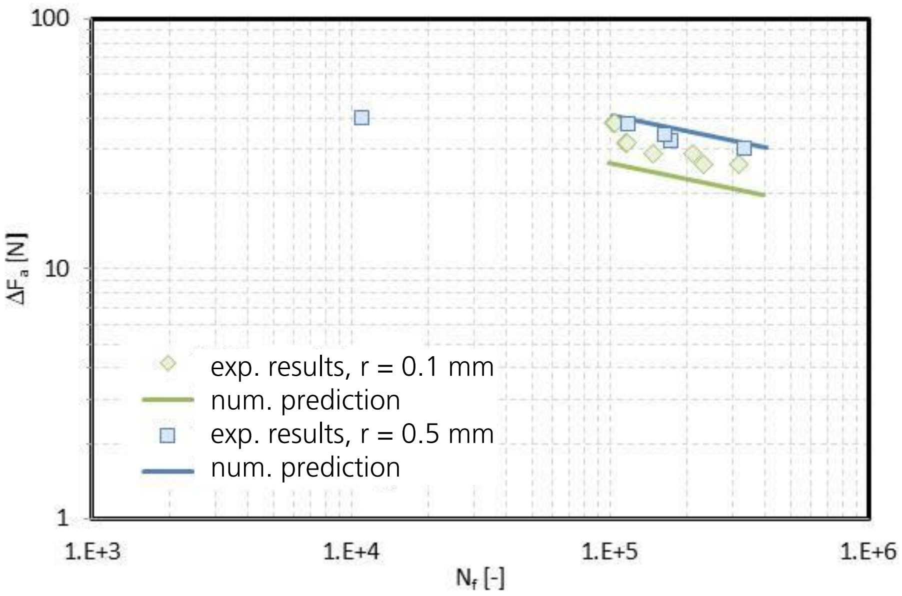
Examples

validation under bending and variable temperature: “T”-specimens

- geometry and loading conditions



- results



➢ good approximation of lifetime by proposed model

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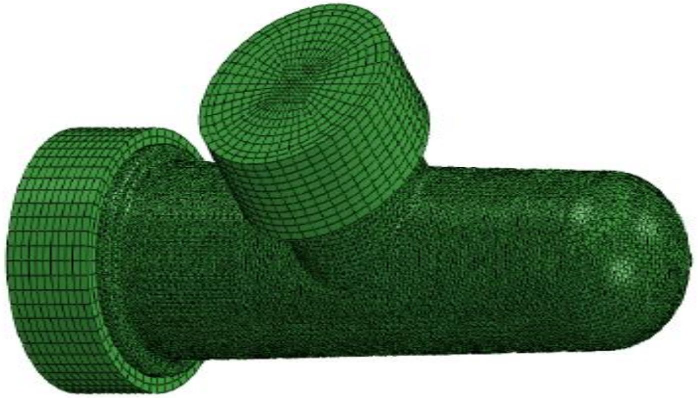
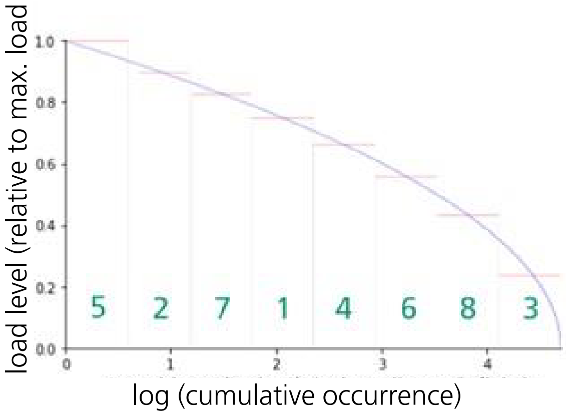
Examples

validation under multi axial loading: “submarine”-specimen

- geometry and loading conditions

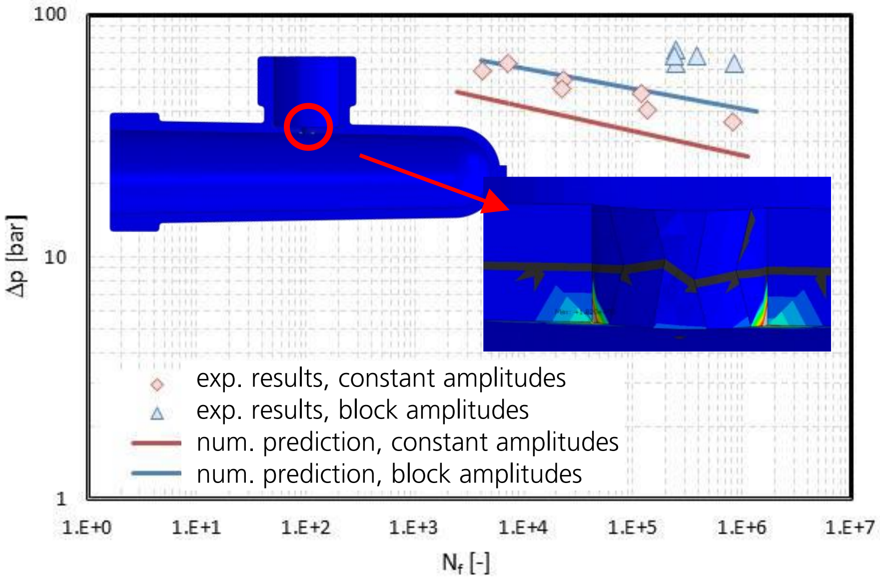




- divided into two internal chambers (interconnected)
- loaded by cyclic internal pressure at ambient temperature

block no.	no. of load cycles	relative amplitude
1	166	0.749164612677923
2	11	0.894628660359632
3	37380	0.235698727762764
4	645	0.660797070405397
5	4	1.00000000000000
6	2495	0.558028733780214
7	43	0.827064354881646
8	9656	0.430947432193174

- results



- ➢ correct prediction of failure spot
- ➢ satisfactory prediction of S-N-curve

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Conclusions

continuum damage model for short fiber composites

- linear elasticity model with anisotropic damage
- strain space defined damage formulation based on single damage variable
- relevant damage mechanisms: pore formation and growth

implementation and validation

- time domain formulation
- user-defined subroutine into commercial FE code
- almost perfect agreement at coupon level
- satisfactory results under more complex loading conditions

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