A damage approach on the fatigue degradation mechanism of biaxial Glass/Epoxy laminates

Fraunhofer IWES

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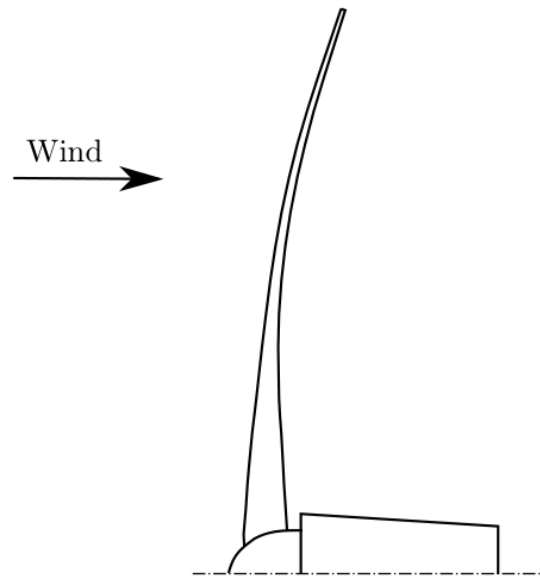
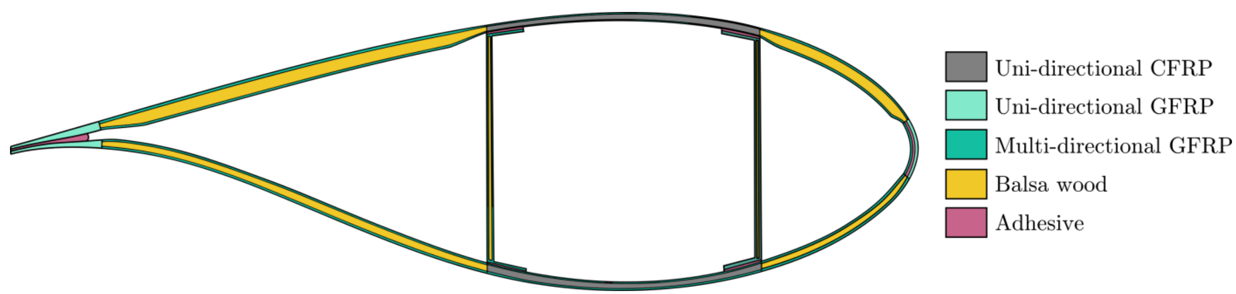
Contents

Introduction

- The Wind Force is imposing the deflection of a Turbine Rotor Blade
- Main stiffness and therefore deflection drivers are the spar caps
- Biaxial laminates follow the deformation imposed from the spar caps
- For Biaxial laminates the blade deflection imposes a displacement controled movement

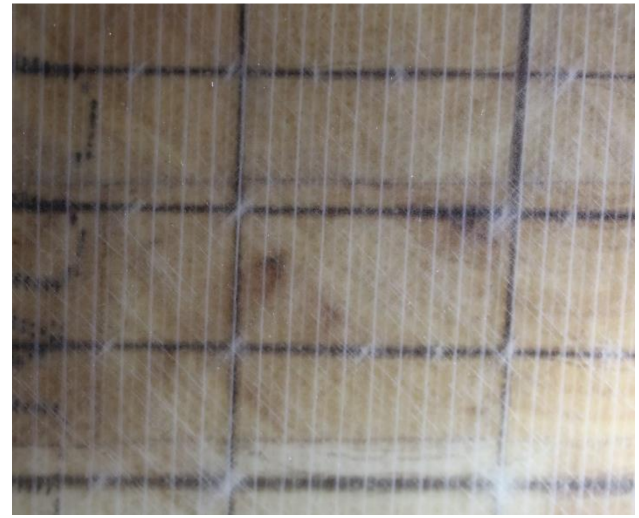




Courtesy: Malo Rosemeier

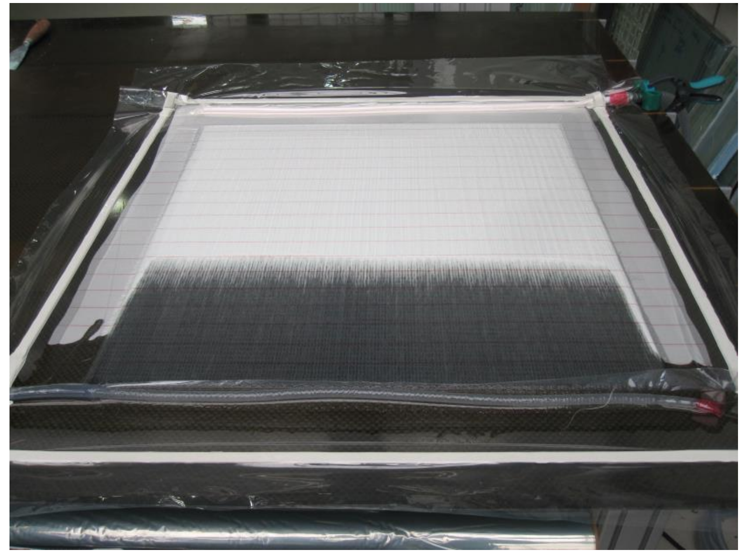
Introduction

- The Biax laminates develop cracks during full scale fatigue test
- When are the crack starting?
- What are they causing?
- Fatigue test campaign of Biax laminate
- Displacement control
- Test termination condition 23% loss of stiffness
- Correlation of crack formation with loss stiffness



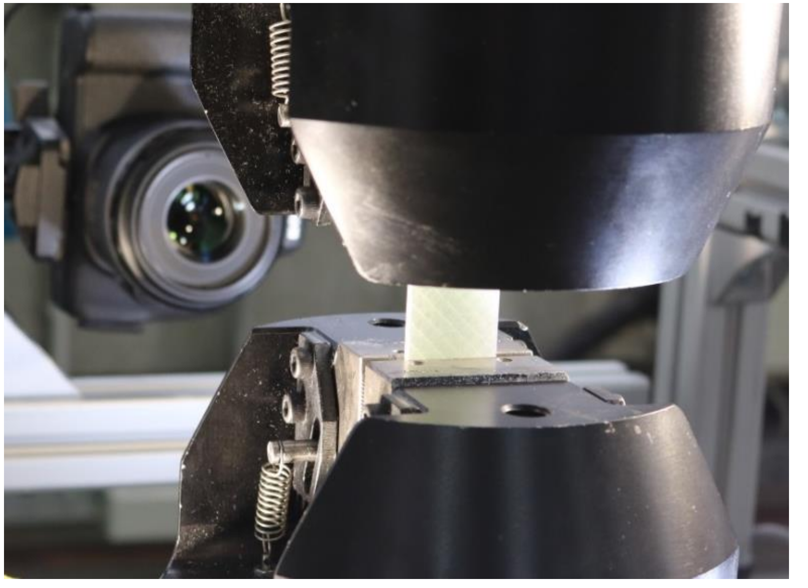
Materials & manufacturing

- Glass/Epoxy
  - Saertex UD 1200 gr/m^2
  - Airstone 880E/Airstone 886H (100:31 mass ratio)
- Matrix degased for 10 mins under vaccum
- VARTM (infusion temp. 45°C)
- Cross-ply stacking sequence
- Coupons cut $[\pm 45]_{2s}$
- Curing: 45°C for 20 hours
- Post-curing: 60°C for 10 hours
- FVF 53%



Experimental setup

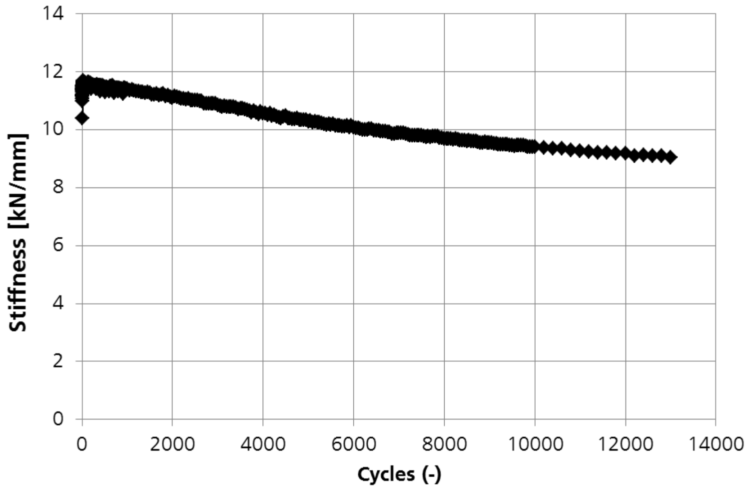
- Fatigue test
  - Tension-tension R=0.1
  - Three max. displ. levels
  - Frequency sweep from 0,5Hz up to test frequency
  - Test frequency depending on the displacement level
  - 25kN coupon machine
  - Displacement controlled (LVDT)
  - Room temperature
  - Test end @ 23% LFS
- Periodic automatic photos at 70% of test max. displacement



- Coupon Geometry
  - Length 27mm (avoid fiber bridging between grips)
  - Width 25mm (prevent buckling)

Analysis

- Stiffness degradation during fatigue
  - Stiffness(Cyc.)
    - $$\frac{\text{Force}_{max} - \text{Force}_{min}}{\text{Displ}_{max} - \text{Displ}_{min}}$$



- Crack density
  - $$\rho_w = \frac{\sum_{i=1}^{n} c_i}{w \cdot L}$$
    - c_i crack length
    - W coupon width
    - L coupon length

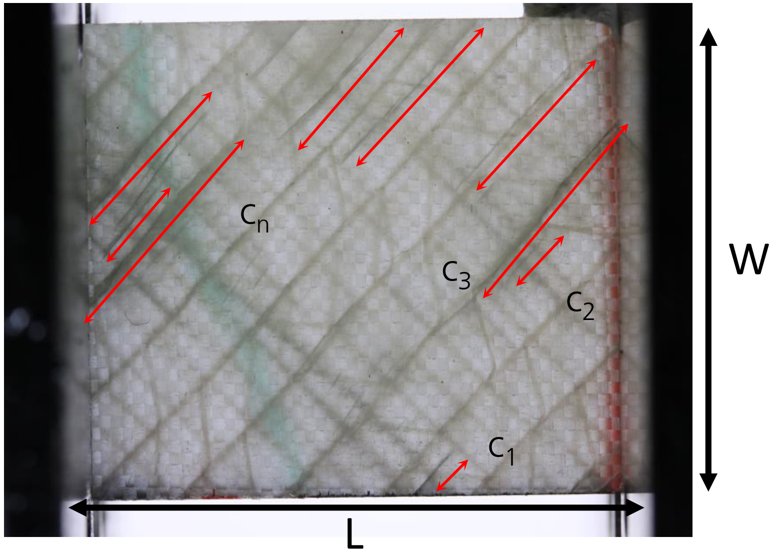
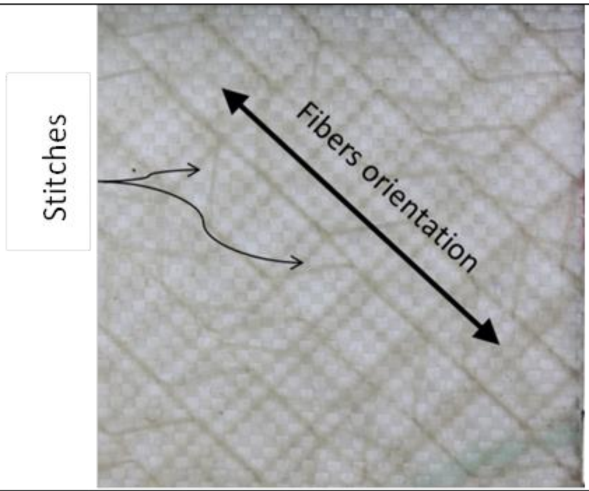
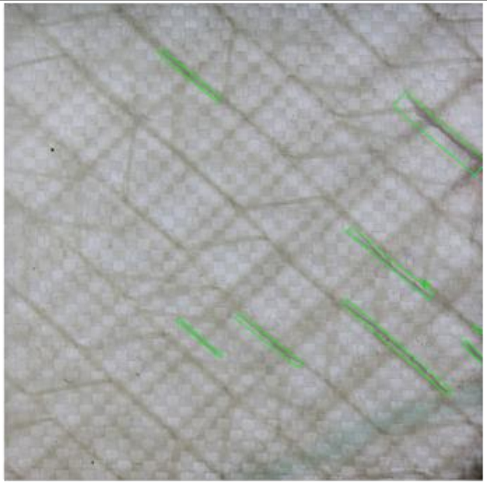
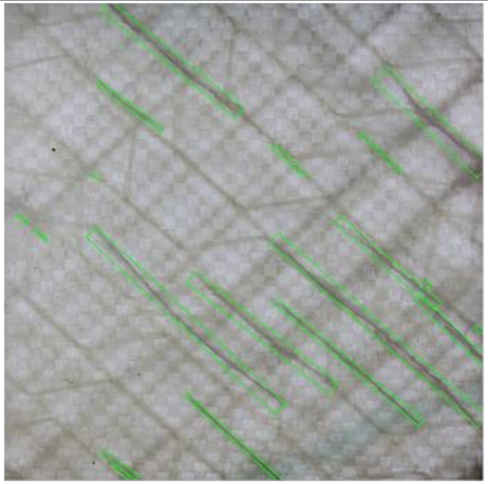


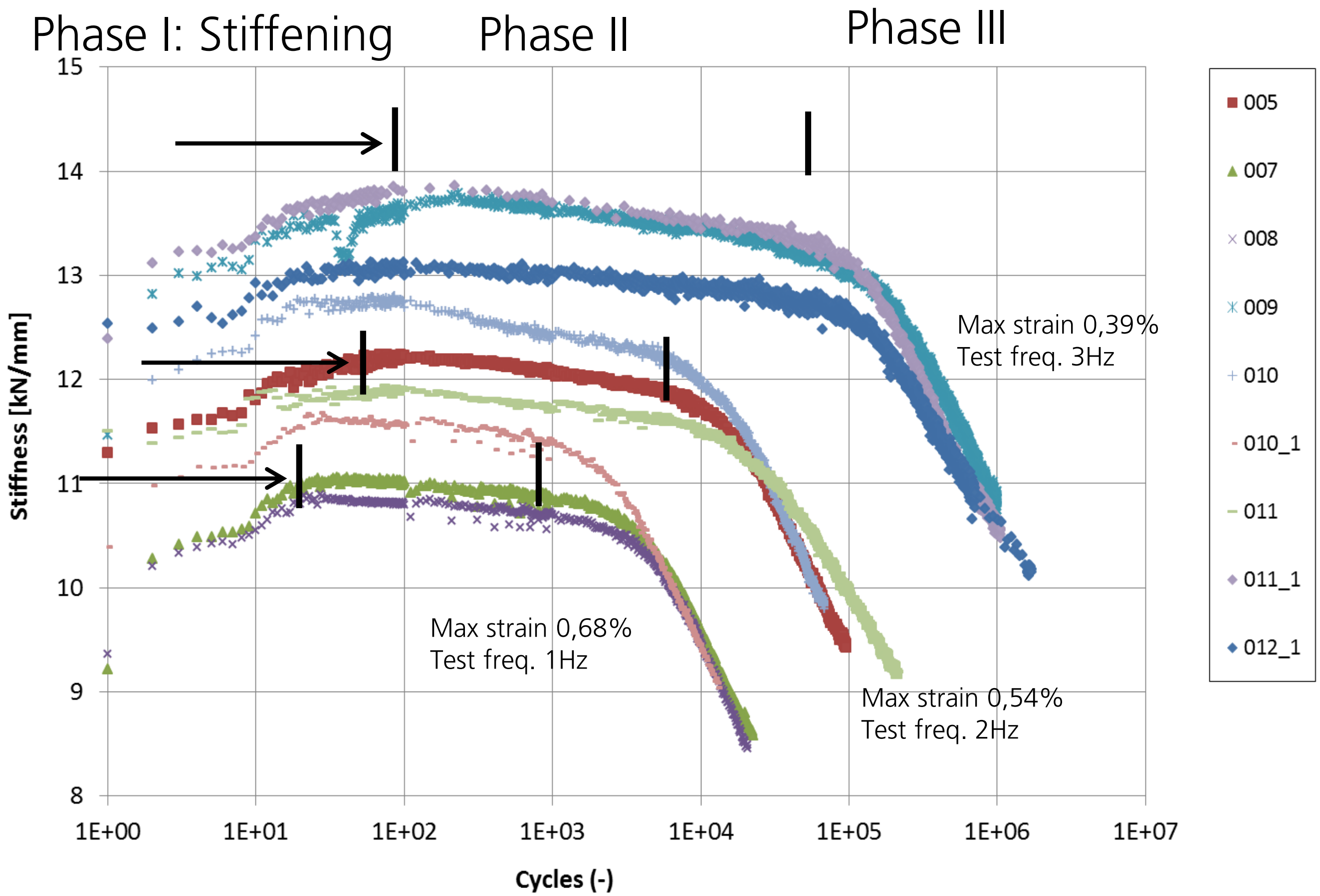
Image Analysis

- Image analysis tool
  - Based on open CV Library
  - Adaptive thresholding method with Gaussian weighting
  - Automatic identification of cracks (subtraction of running photo from reference photo)
  - Automatic calculation of the crack density

Cycles	0	170.000	370.000
			
ρ_W	0	7,78E-04	2,17E-03

Loss of Fatigue Stiffness (LFS)

- Stiffness degradation during fatigue (cycle: logarithmic scale)



Loss of Fatigue Stiffness (LFS)

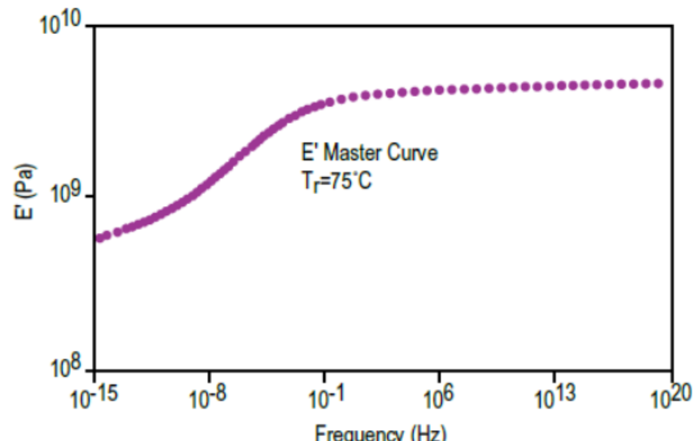
- Stiffness degradation during fatigue

Phase	Start cycle	End cycle	Description	Effect
I	0	10-200 (depending on the freq.sweep)	Stiffening	Viscoelastic effect of the resin

- Fatigue test frequency sweep characteristics

No of Coupons	Frequency	Sweep rate	Sweep duration
[-]	*[Hz]*	*[Hz/sec]*	*[Cycles]*
3	*1*	*0,025*	*36*
3	*2*	*0,025*	*76*
2	*3*	*0,025*	*116*
1	*5*	*0,025*	*196*

- Resin viscoelastic performance



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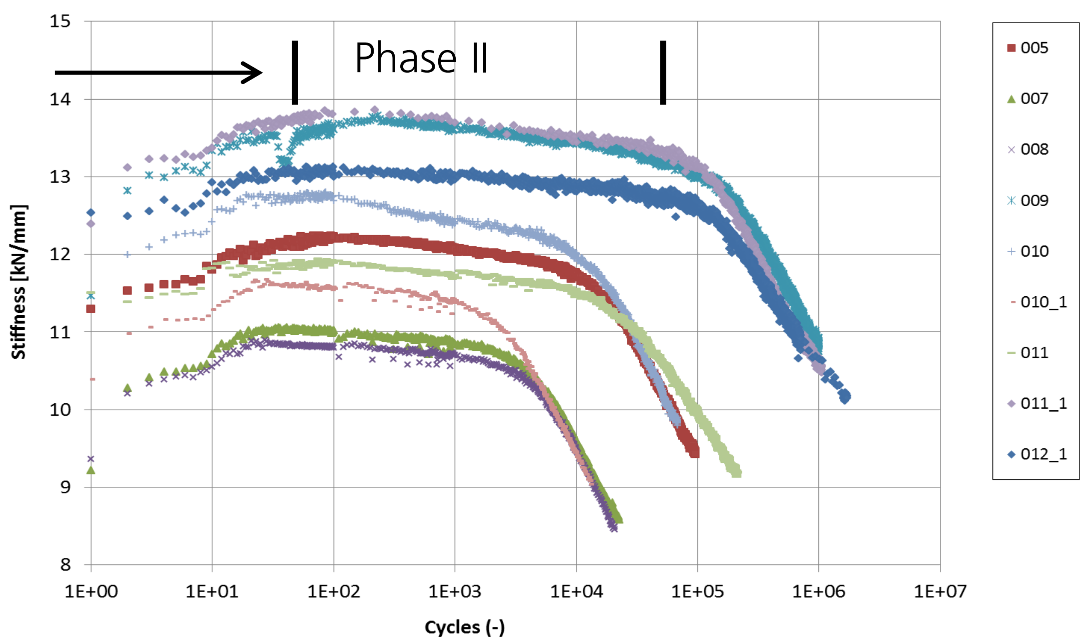
Loss of Fatigue Stiffness (LFS)

- Stiffness degradation during fatigue

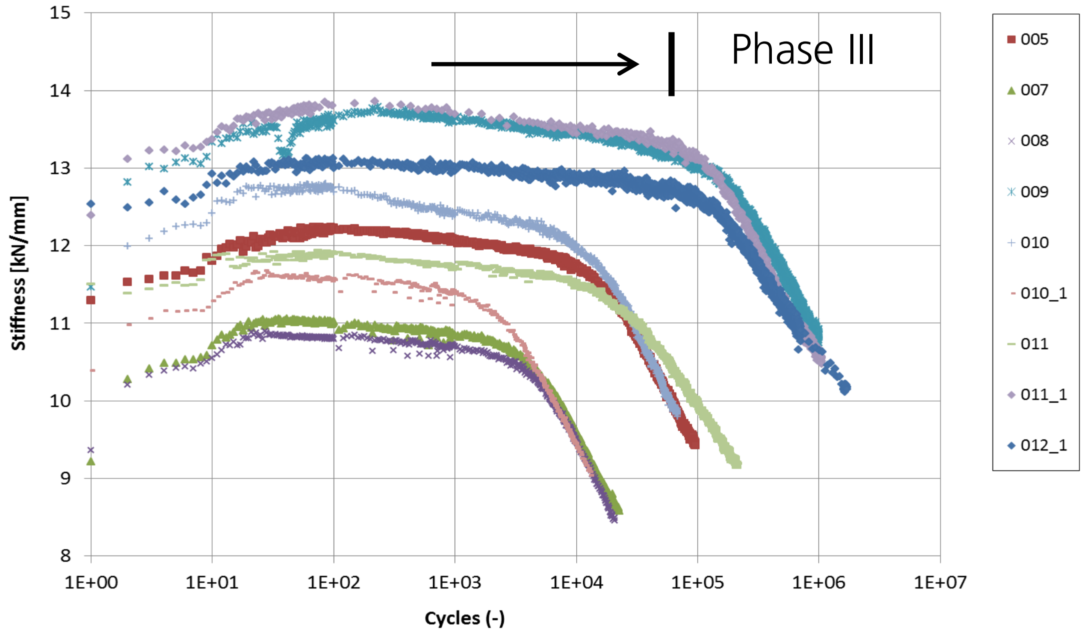
Phase	Start cycle	End cycle	Description	Effect
II	10-200 cycles	≈5% of fatigue life	Moderate stiffness degradation ≈3,3%	Microcracking (not visible)



Loss of Fatigue Stiffness (LFS)

- Stiffness degradation during fatigue

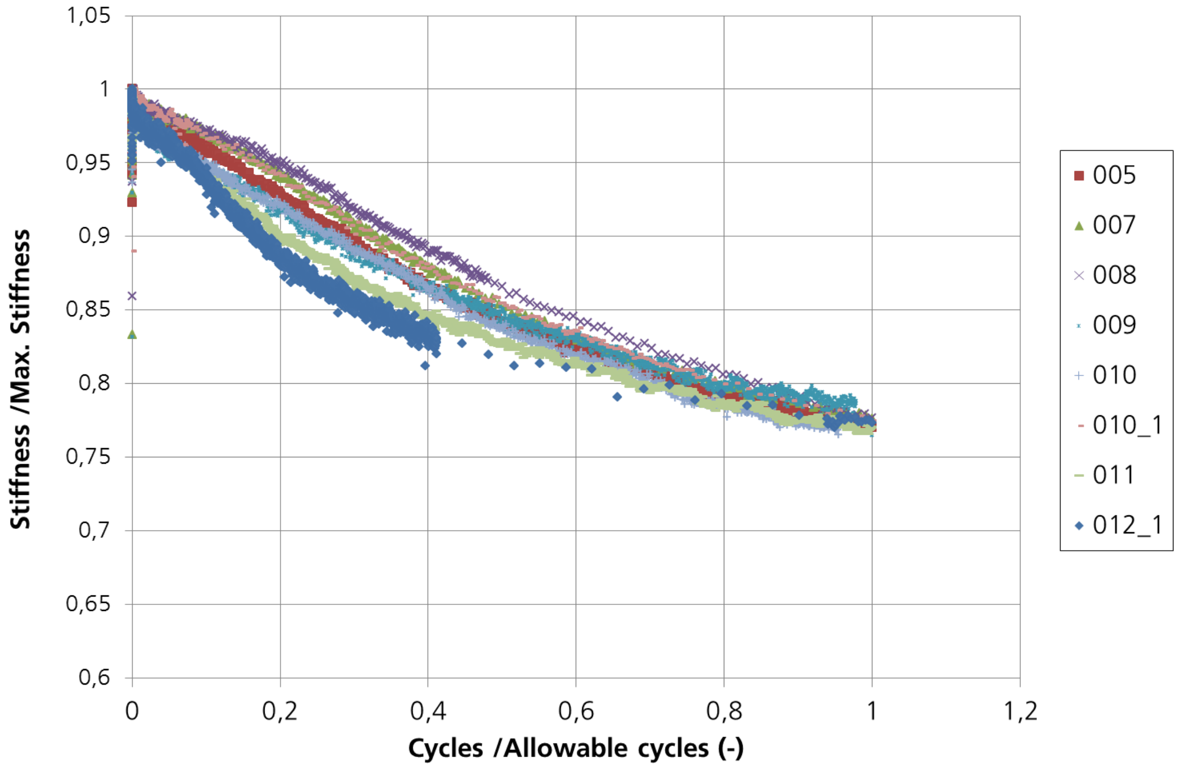
Phase	Start cycle	End cycle	Description	Effect
III	After first visual crack	23% of Stiffness Loss	Major stiffness degradation	Macroscopically visible cracks



Loss of Fatigue Stiffness (LFS)

- Stiffness degradation during fatigue (both normalized to unity)

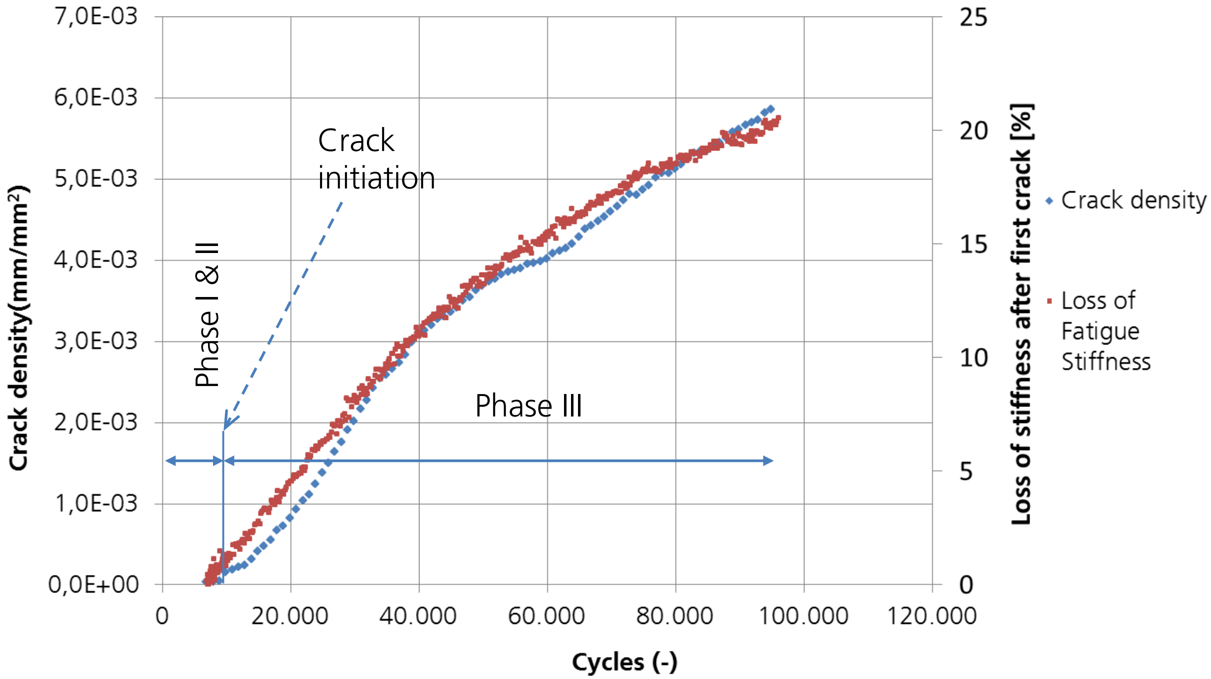
  - Stiffness degradation is correlated to the fatigue life ratio
  - When stiffness degradation is known then the fatigue life ratio could be calculated
  - All tests show similar performance



Loss of Fatigue Stiffness (LFS)

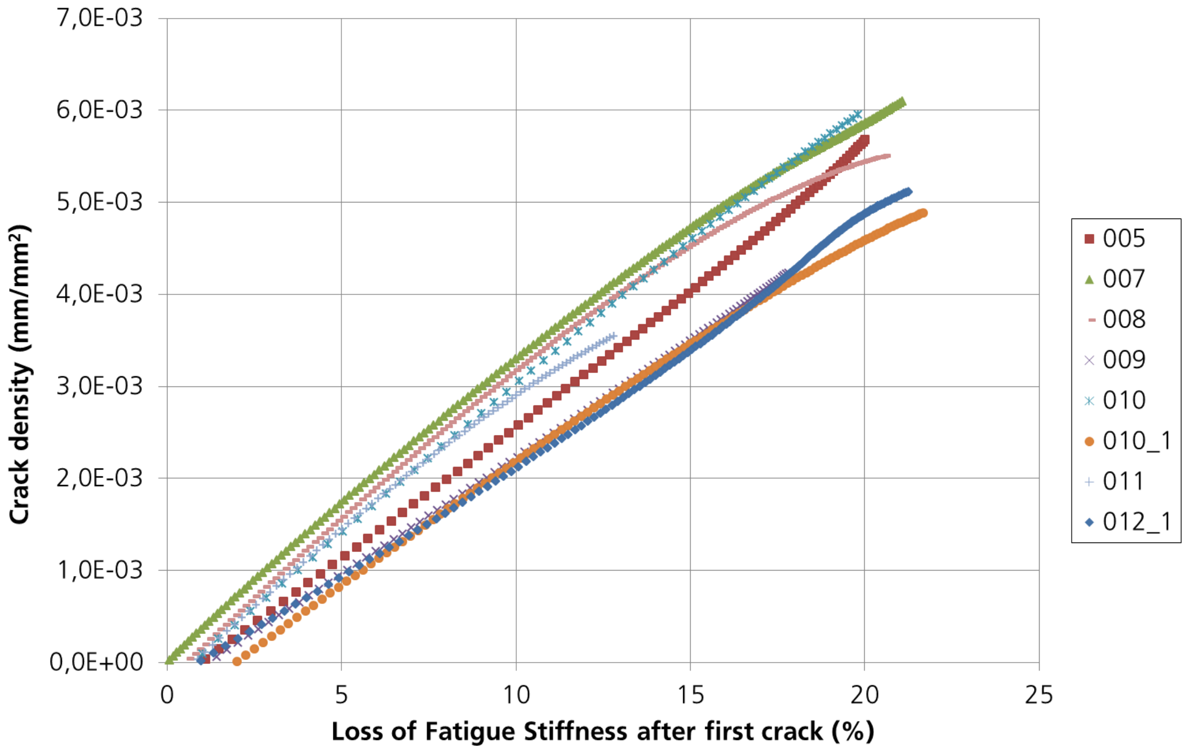
- Relative stiffness degradation & crack density during fatigue

  - Caclulation of relative loss of stiffness only in phase III
  - Linear relation between relative loss of stiffness and crack density



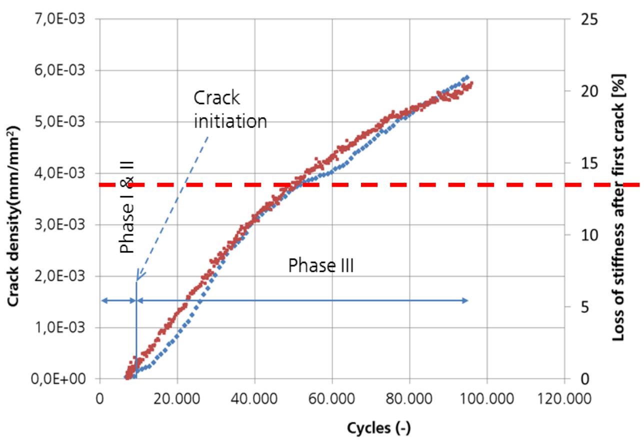
Loss of Fatigue Stiffness (LFS)

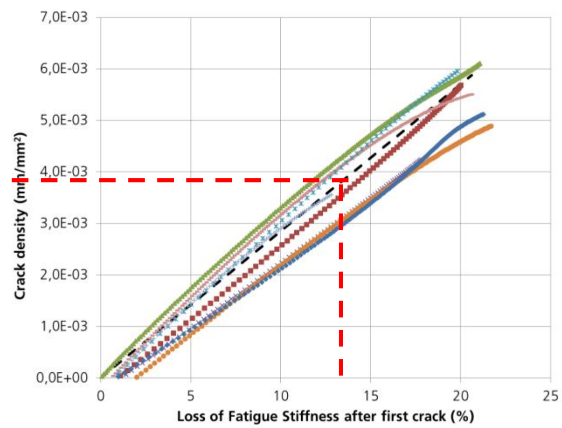
- Relative stiffness degradation during fatigue and crack density
  - Caclulation of relative loss of stiffness only in phase II
  - Linear relation between relative loss of stiffness and crack density

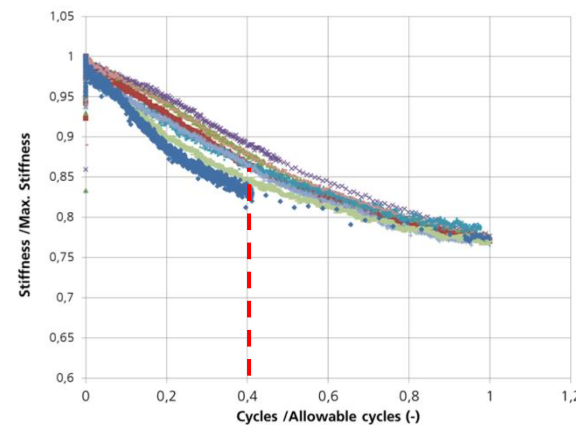


Loss of Fatigue Stiffness (LFS): Case Study

- Loss of stiffness only after crack initiation
- Linear relation between crack density & LFS
- Unique formulation for the description of normalized fatigue cycle (NFC) number vs. norm. LFS after 1st crack







- Given crack density $3{,}82 \cdot 10^{-4}$
- Stiffness Loss of 13,4%
- Specific life cycle ratio 49,6%

Loss of Fatigue Stiffness (LFS) : Case Study

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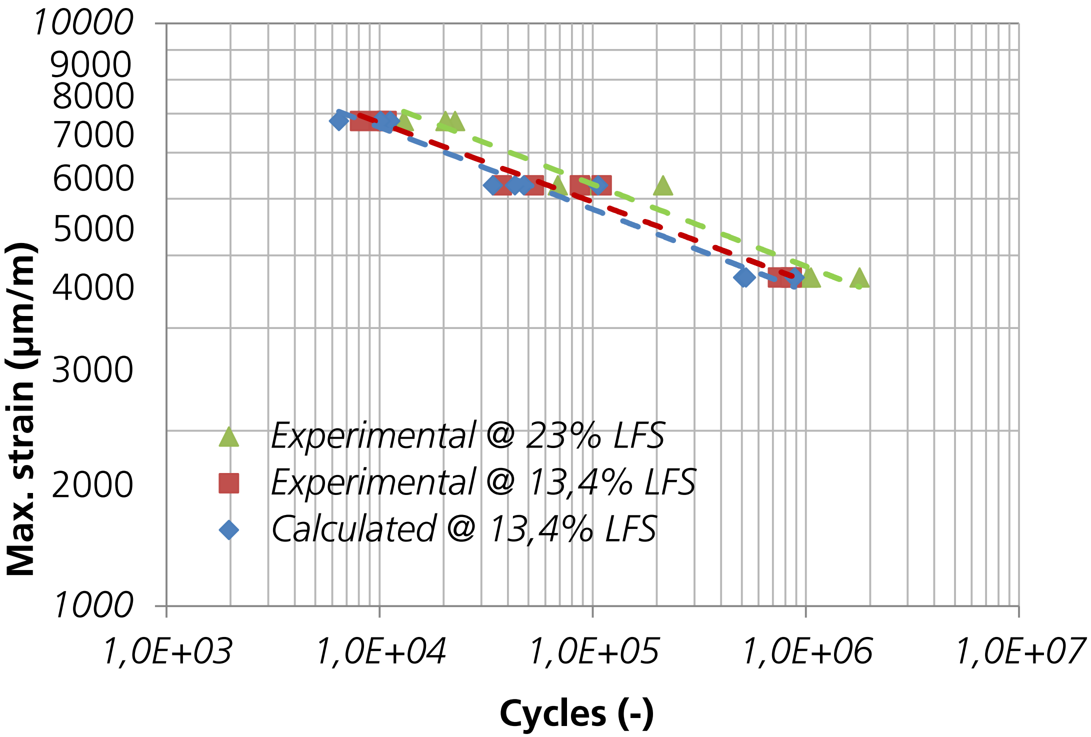

- Material fatigue performance @ 13,4% LFS

  49,6%·e/N @ 23%

- Remaining life can be calculated

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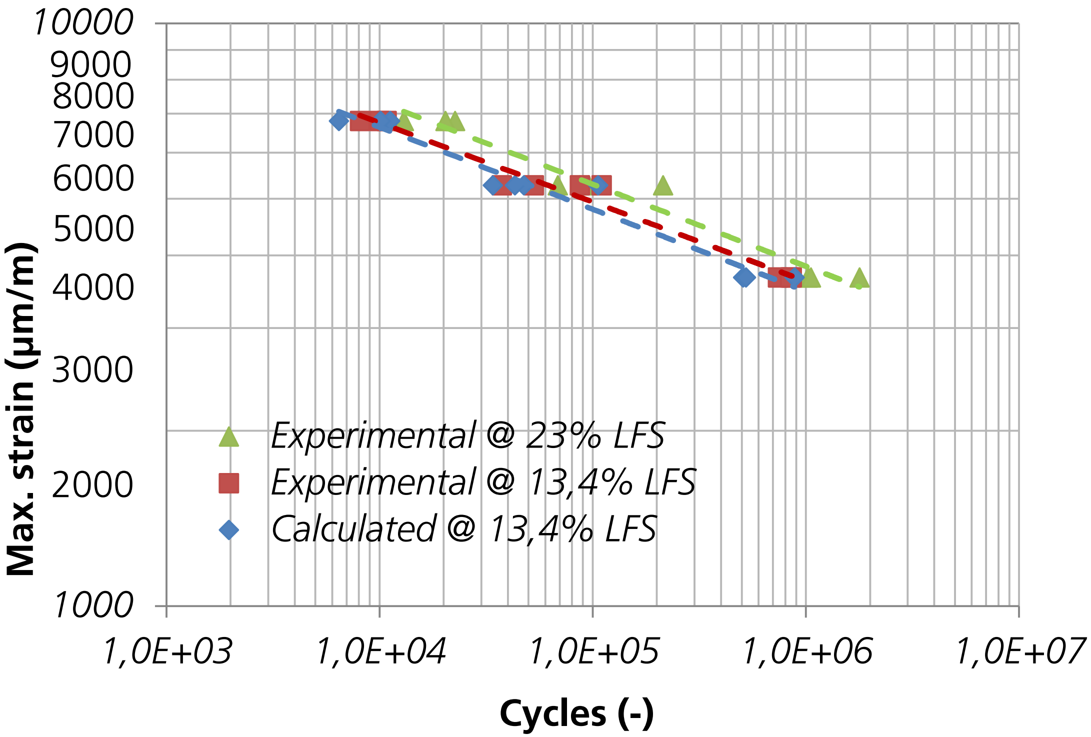

- e/N parameters= f(crack density)

$$e = A \cdot N^b$$

LFS	A	b
23% (exp.)	26790	-0,141
13,4% (exp.)	23678	-0,136
13,4% (calc.)	24268	-0,141

Loss of Fatigue Stiffness (LFS) : Case Study

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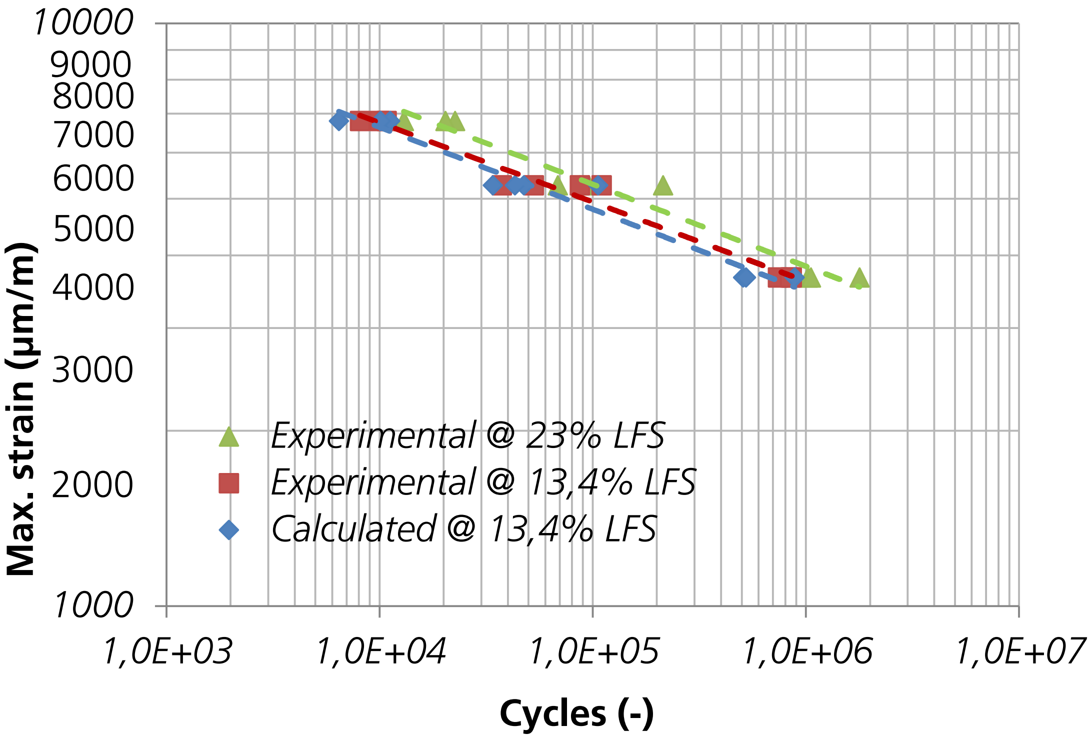

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Summary

- The damage evolution of a Biax $[\pm 45]_{2s}$ laminate configuration was investigated during displacement controlled fatigue test (R=0.1)
- Matrix cracking parallel to the fibers direction was tracked with high resolution photos
- For the derivation of the developed crack density, automatic image processing was performed with an in-house developed tool
- It was evident that the developed cracks (macroscopically visible) are responsible for the stiffness degradation along the load axis
- Before the development and recognition of the macroscopic visible cracks, all coupons showed an average stiffness reduction of around 3%. This was attributed to microckracks
- The Fatigue Stiffness degradation form was similar for all specimens when plotted over fatigue cycles in a normalized to unity scale
- The experimentally measured crack density correlates directly to the the run cycle number ratio

Summary

- Provided a characterized e/N curve, remaining life of a coupon can be calculated with limited uncertainty

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Thank you for your attention

Any questions?

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