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Methodology for fatigue damage prediction in NCF composites for applications in aircraft engines

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GKN AEROSPACE

swerea | SICOMP

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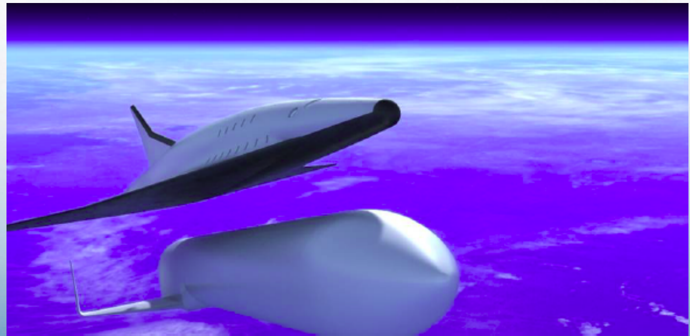
Composites

- Polymer composites: materials of the future
- Constituents: glass, carbon fibers, epoxy resin
- High specific stiffness and strength
- Superior fatigue life and performance
- Applications in aerospace, aircraft, wind power industries, etc.



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Introduction

- The unparalleled specific stiffness and strength have made polymer composites an obvious choice in aircraft engines
- Modern turbofan engines contain composites in total weight share of 10-30%.

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VITAL DEMO 2008
single aisle size

Introduction

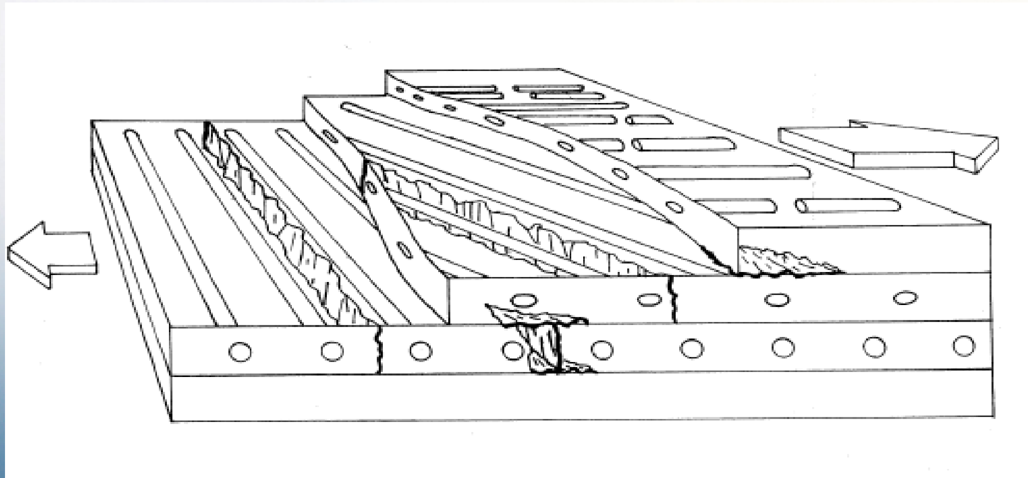
- GKN Aerospace Engine Systems develops technology for design and manufacturing of composite structural for commercial and military aircraft engines
- Important part in this development is to create an understanding for material behavior and models that can reliably predict structural behavior and function

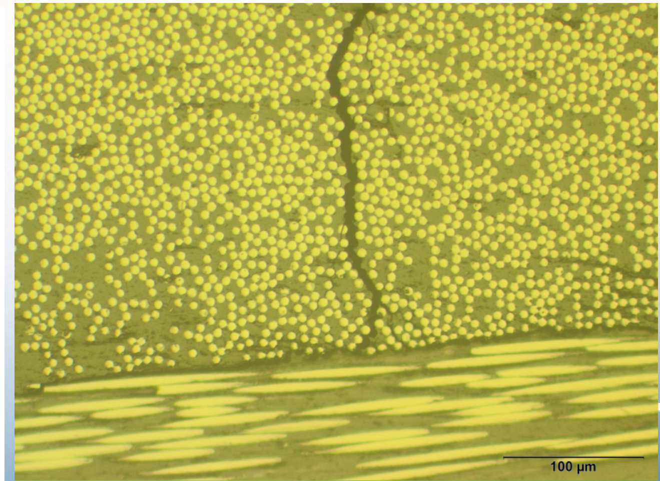
GKN AEROSPACE

VITAL DEMO 2008
single aisle size

Transverse cracks and delaminations

- Transverse cracks and delaminations develop in the plies of laminated composites during the service life
- Thermo-elastic properties of the laminate are degraded
- Damage propagation determines final failure and fatigue life
- Complex evolution of damage



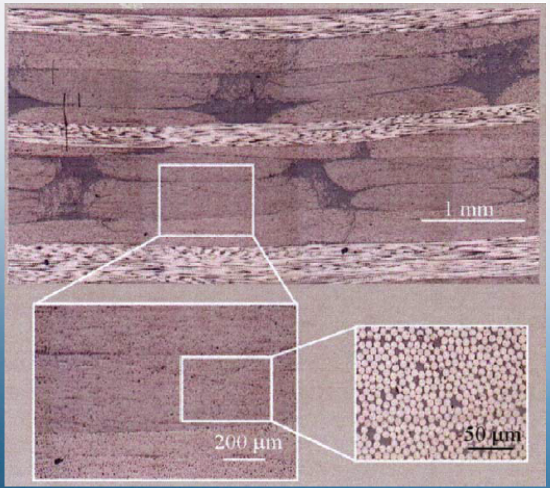


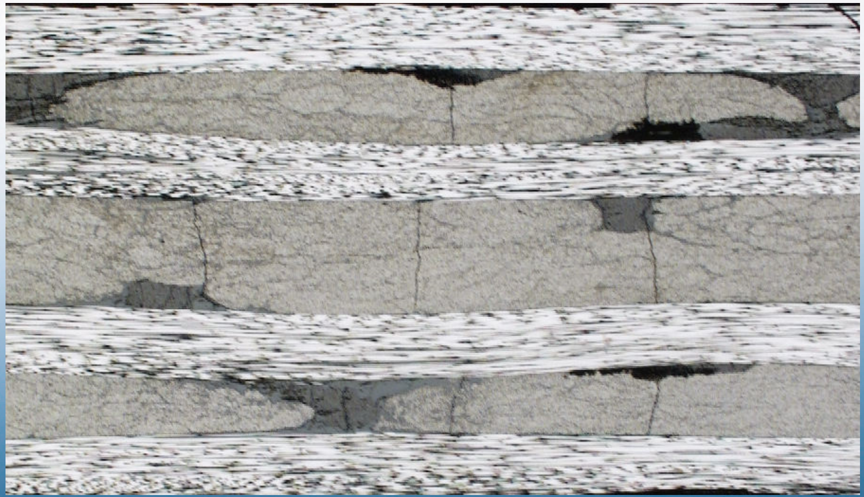
Project

- Methodology to design composite structures resistant to intra- and interlaminar damage. NFFP6 project, acronym: MERINDA
- Duration: September 2014 – September 2017
- Collaboration between Luleå University of Technology, Swerea SICOMP and GKN Aerospace

Objective

- Develop new methodology for prediction of initiation and evolution of damage in non-crimp fabric (NCF) composites for aircraft aero engine applications
- Focus: Initiation and evolution of transverse cracks under mechanical fatigue loading



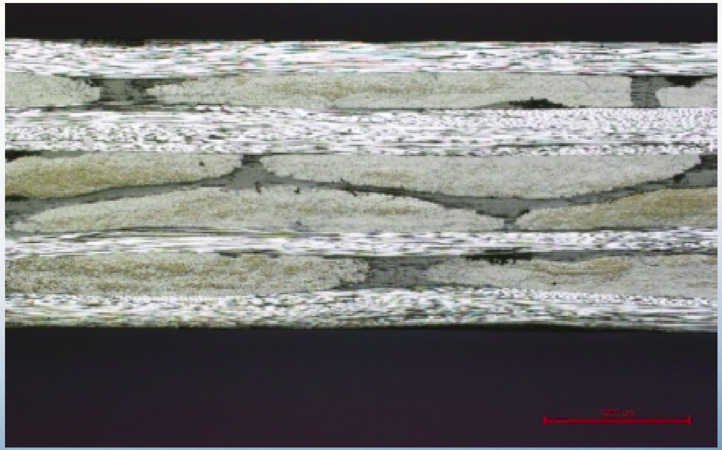


Mattsson et al, Composites Part B, 2007

Material

- Carbon fibre\epoxy resin laminates, manufactured from unidirectional Non Crimp Fabrics (NCF)
- Bundle thickness 0.25mm, width 3.5mm
- Lay-ups: $[0/90]_S$, $[+45/0/-45/90]_S$, $[+45/0/-45/90]_{2S}$
    - Layer properties

E_L	[GPa]	120
E_T	[GPa]	9.18
G_{LT}	[GPa]	3.94
ν_{LT}	[-]	0.311
α_L	[1/°C]	3.20E-07
α_T	[1/°C]	3.16E-05



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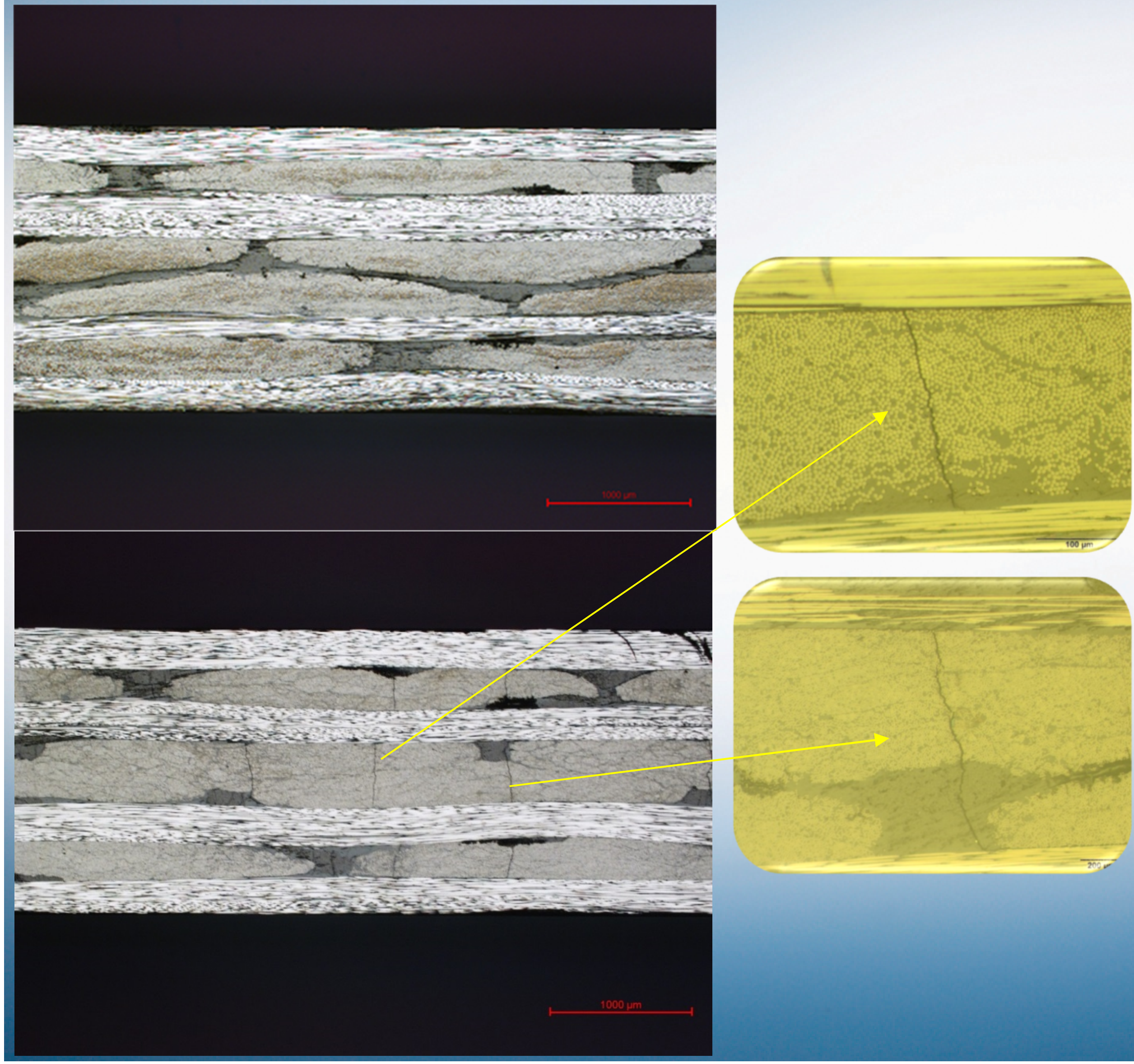
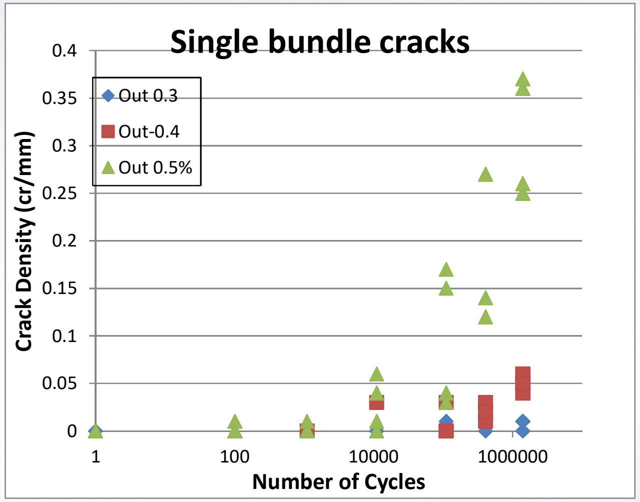
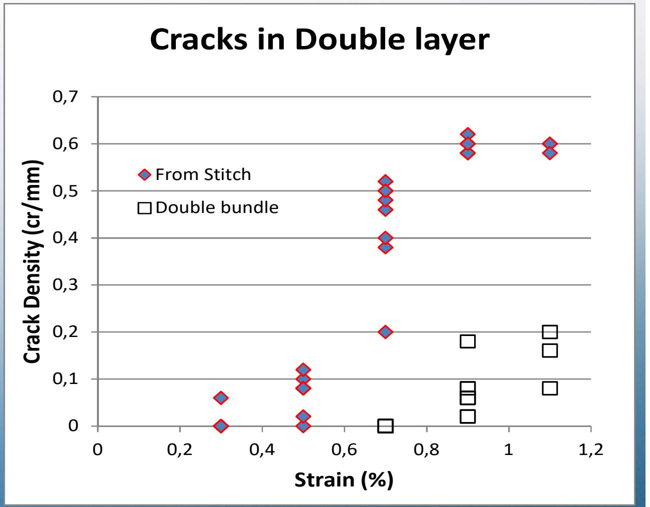
Micro-damage in NCF composites

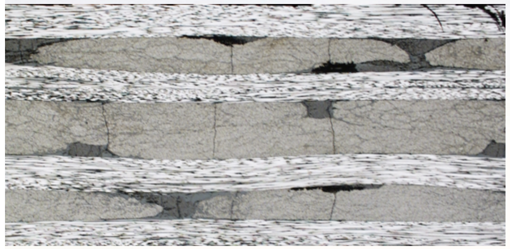






Experimental work

- Lay-ups:
  - $[0/90]_S$
  - $[+45/0/-45/90]_S$
  - $[-45/90/+45/0]_S$
  - $[+45/0/-45/90]_{2S}$



Quasi-static tensile tests								
Applied strain level ε (%)								
0.3	0.4	0.5	0.7	0.9	1.1	1.3	1.5	...

$\rho_c(\sigma)$

Tension-tension fatigue tests,								
Applied max. strain levels ε **= 0.4%,** ε **= 0.5%**,etc. R = 0.1, f=5Hz								
Number of cycles								
1	10	50	100	10^3	10^4	10^5	10^6	...

$\rho_c(N, \sigma_{\max})$

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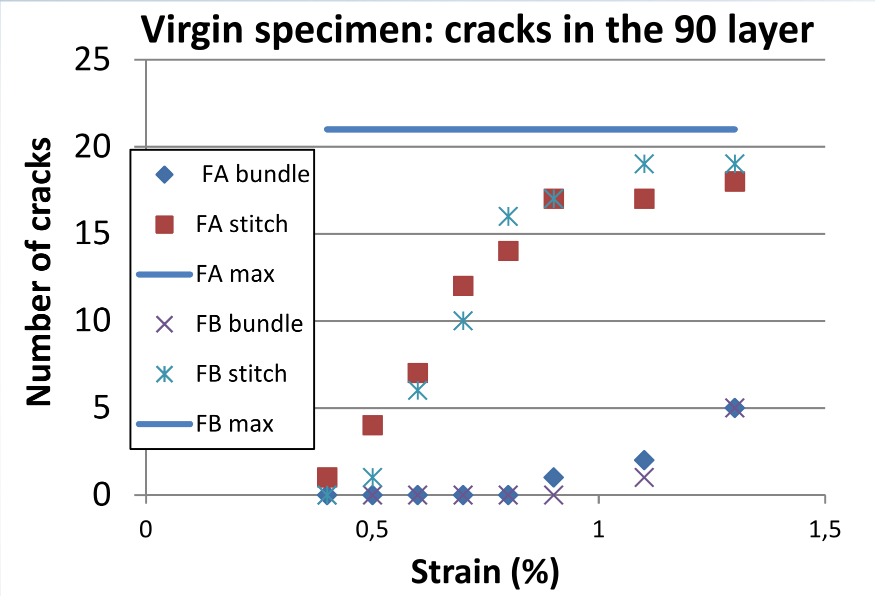
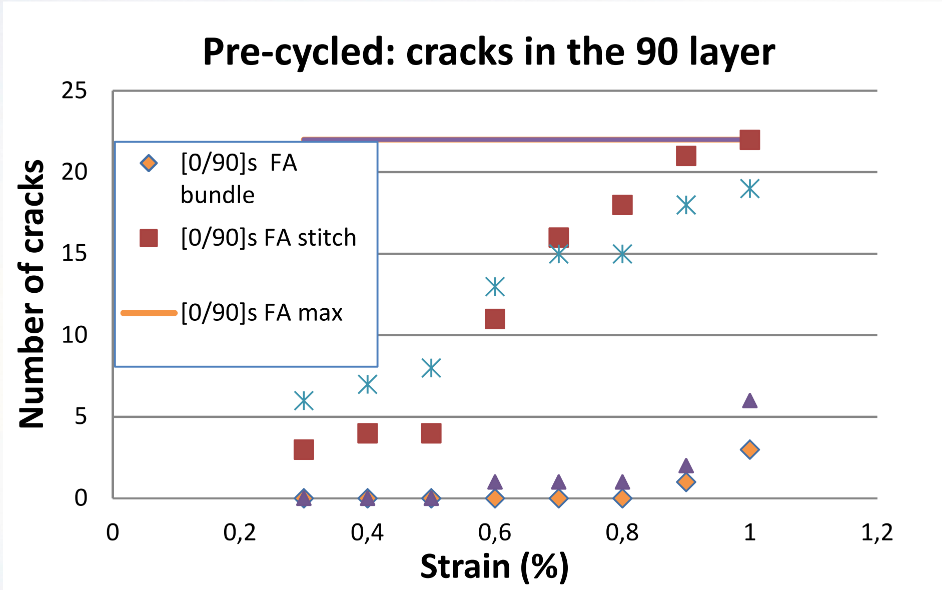
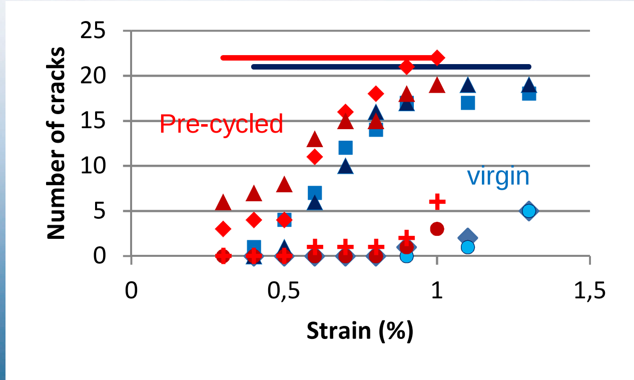
Damage development in quasi-static tension $[0/90]_s$





Pre-cycled = 1 million load cycles at 0.2% max strain



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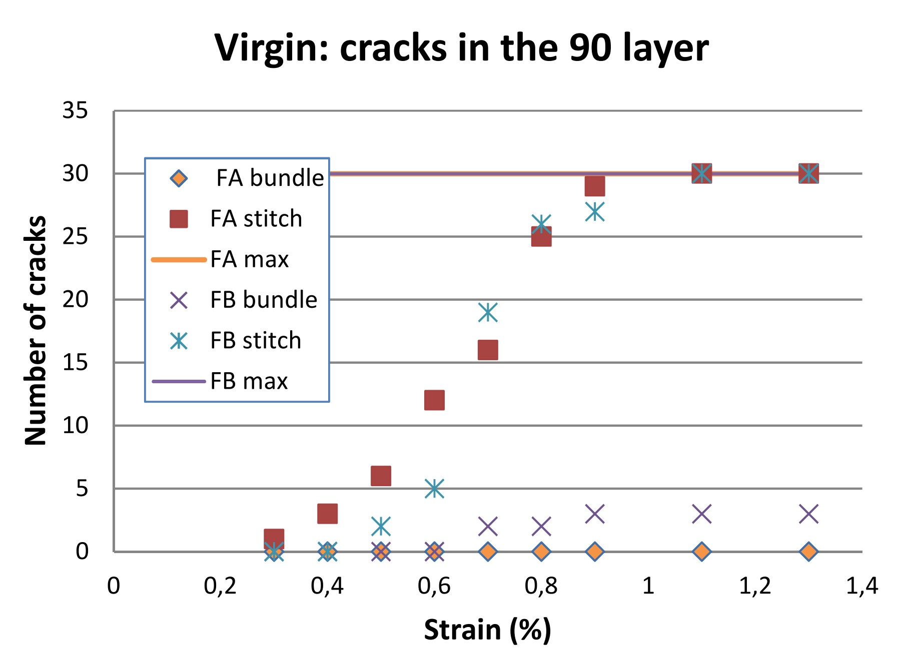
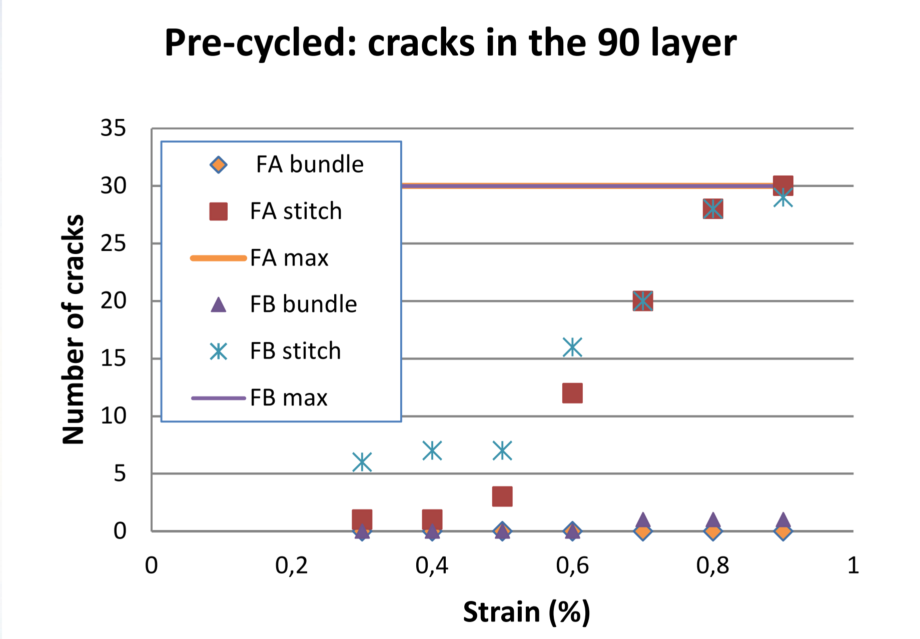
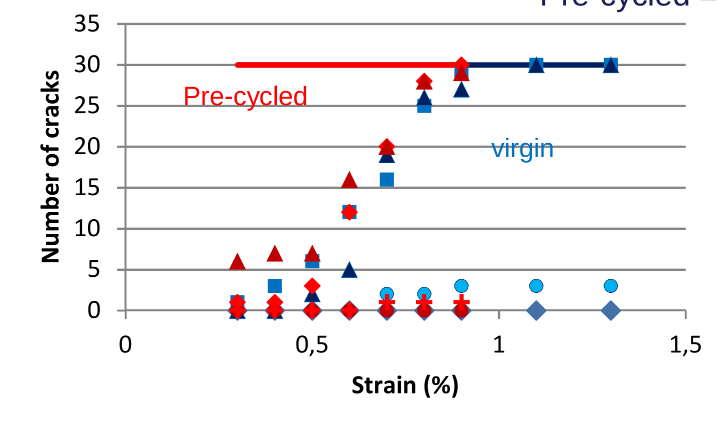
Damage development in quasi-static tension $[45/0/-45/90]_s$





Pre-cycled = 1 million load cycles at 0.2% max strain



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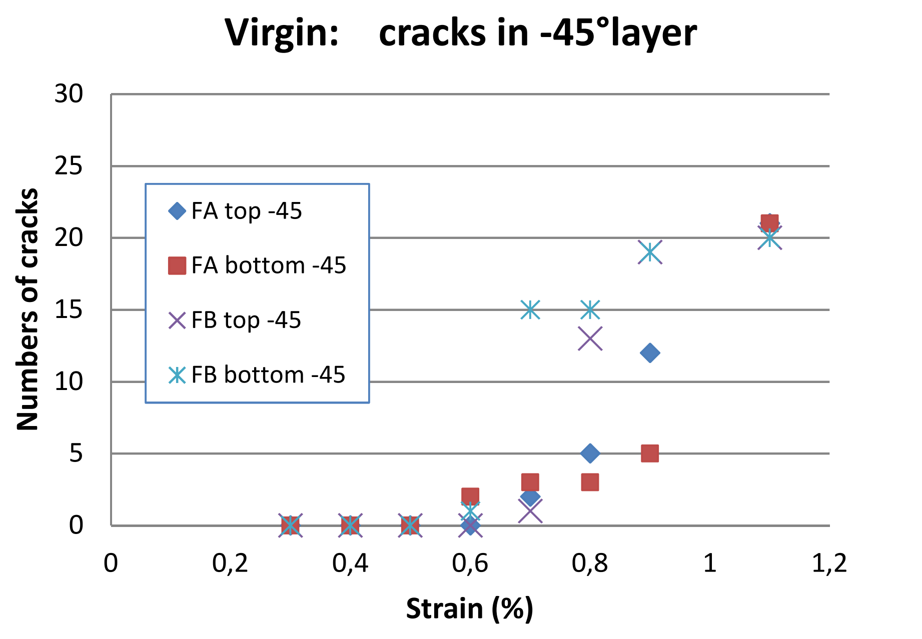
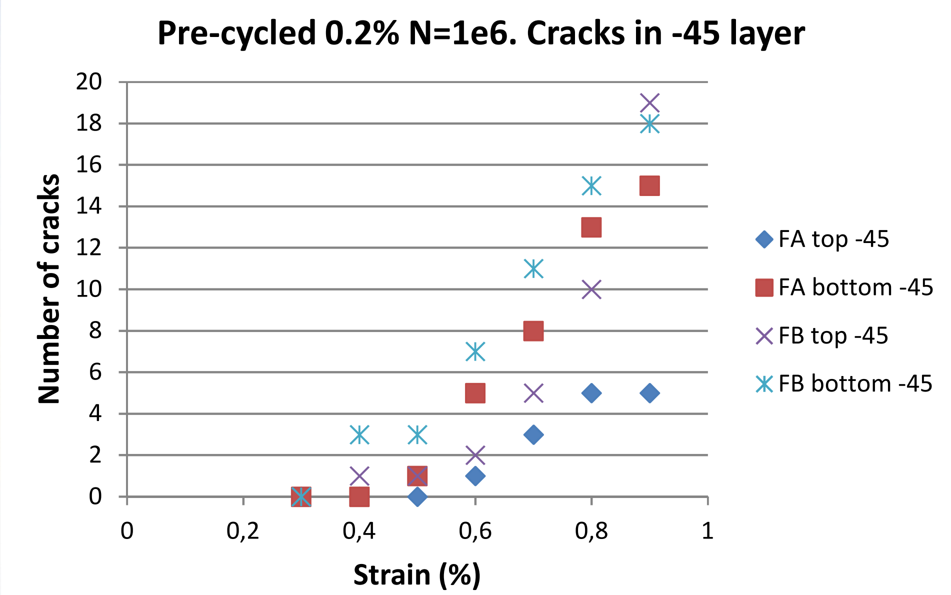
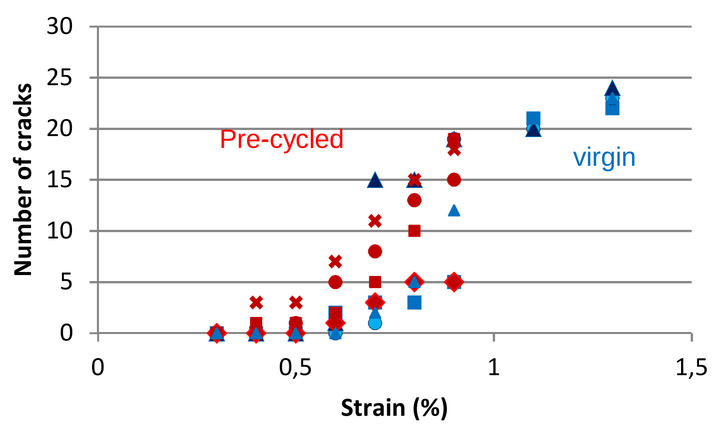
Damage development in quasi-static tension $[45/0/-45/90]_s$





Pre-cycled = 1 million load cycles at 0.2% max strain



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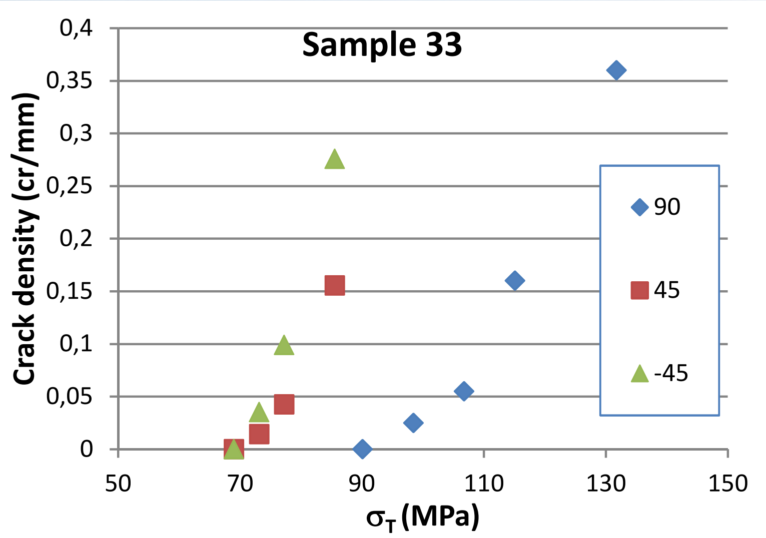
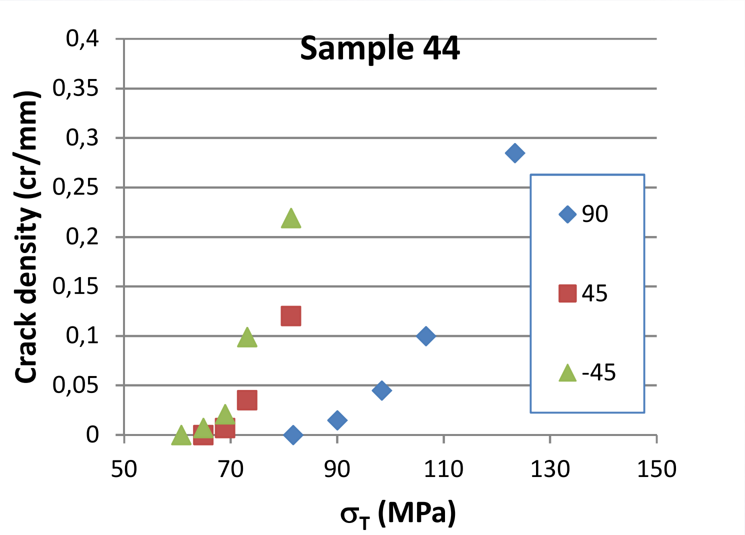
Damage development in quasi-static loading $[-45/90/45/0]_s$



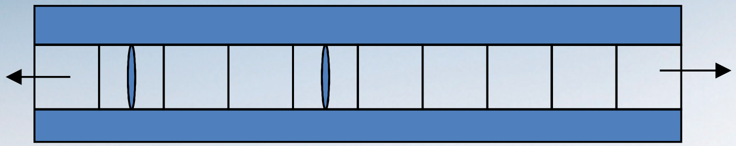


- Transverse stress σ_T in layers found using laminate theory: mechanical stress + residual thermal stress

$$\sigma_T = \sigma_{mech} + \sigma_{th}$$

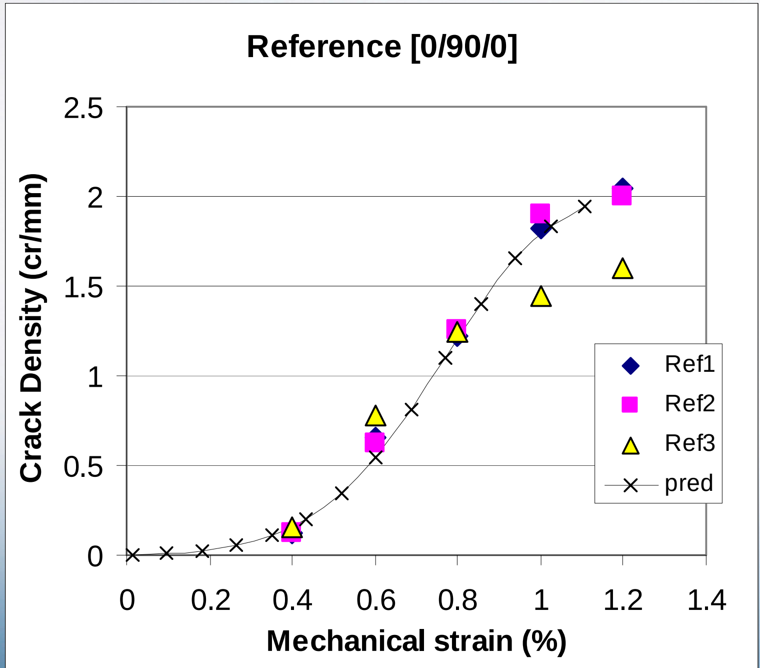
$$\Delta T = 180°C - 23°C = 157°C$$

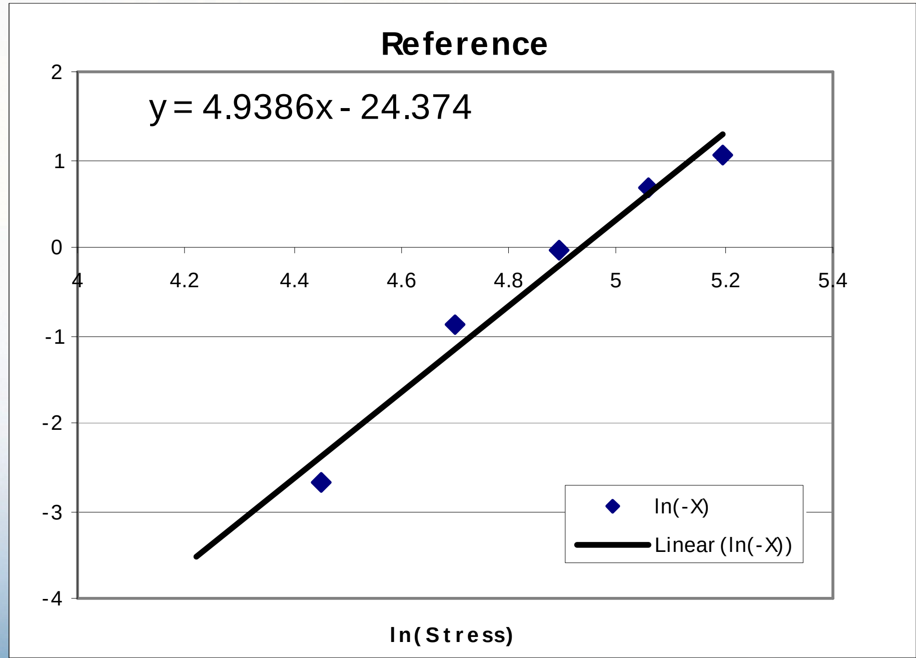
Weibull analysis



$$P_f(\sigma) = \frac{M_{failed}(\sigma)}{M} \qquad P_f = 1 - \exp\left(-\left(\frac{\sigma}{\sigma_0}\right)^m\right)$$

σ_0, m Weibull parameters





- Monte-Carlo simulations are preferable

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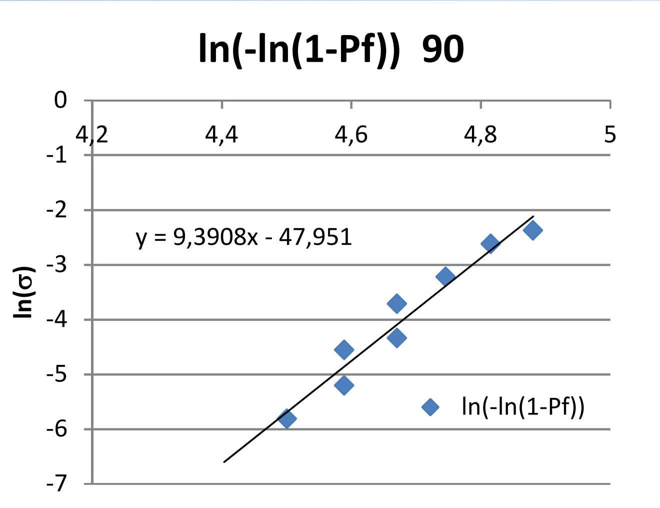
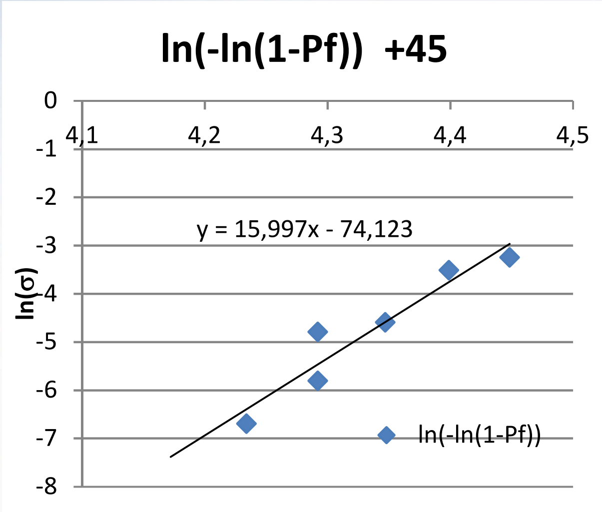
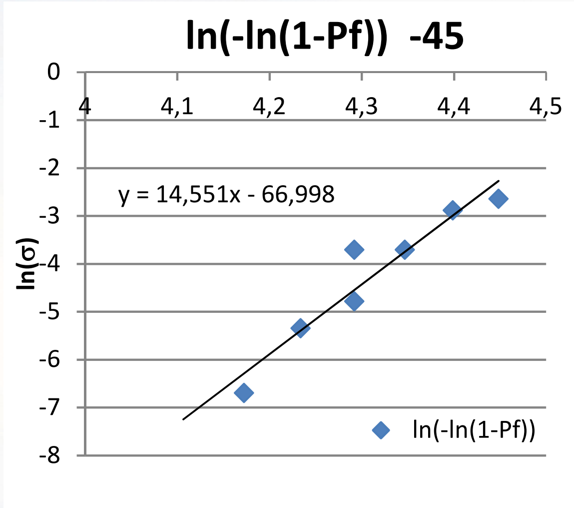
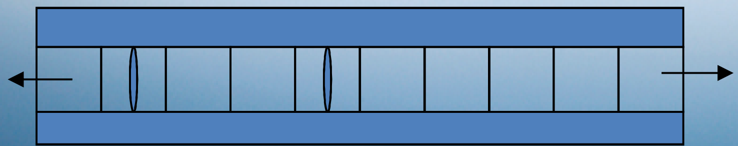
Damage development in quasi-static loading $[-45/90/45/0]_s$







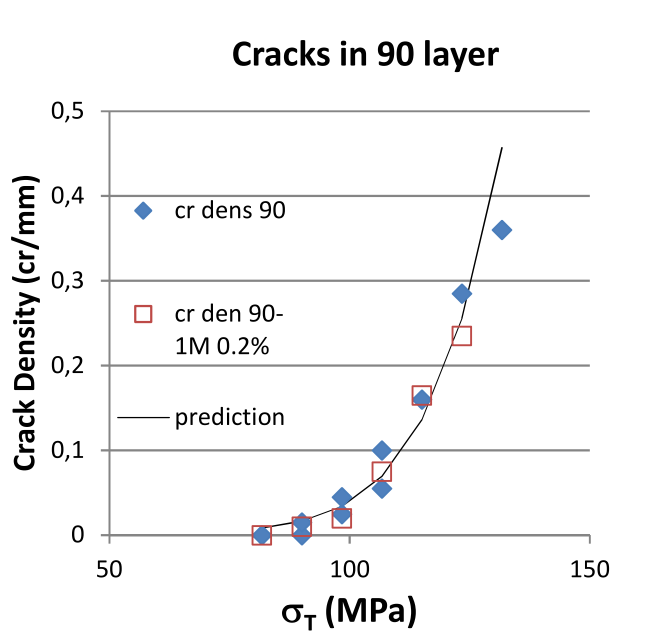
$$P_f(\sigma) = \frac{M_{failed}(\sigma)}{M} = \frac{\rho_c(\sigma)}{\rho_{c,\max}} \qquad P_f = 1 - \exp\left(-\left(\frac{\sigma}{\sigma_0}\right)^m\right)$$

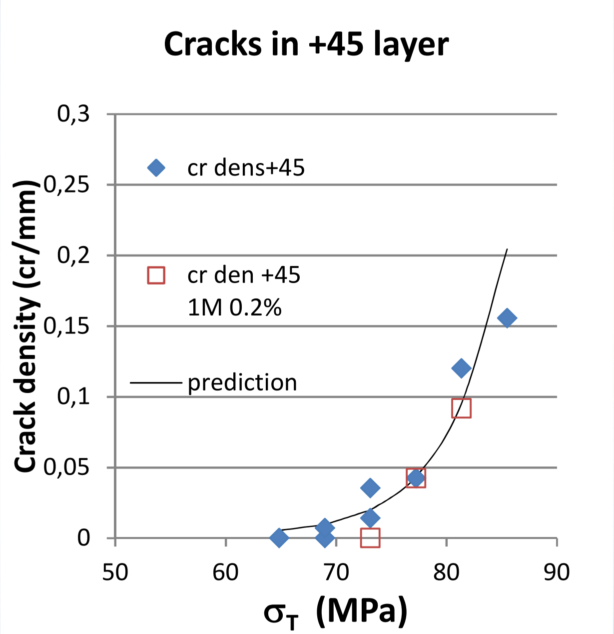


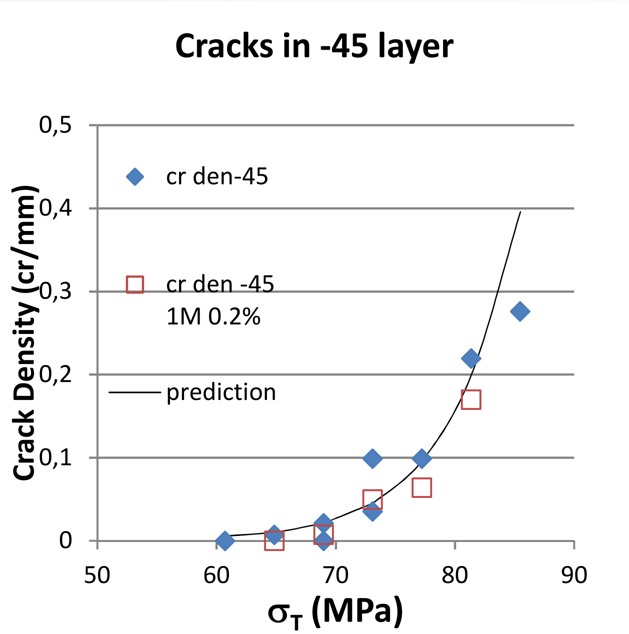
	90 layer	45 layer	-45 layer
σ_0	165.04	102.88	99.92
m	9.39	15.99	14.55

	90 layer	45 layer	-45 layer
σ_0	152.91	103.51	93.72
m	11.93	15.75	20.98

Damage development in quasi-static loading $[-45/90/45/0]_s$







$$P_f = 1 - \exp\left(-\left(\frac{\sigma}{\sigma_0}\right)^m\right)$$

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Hypothesis

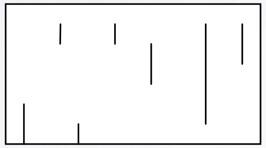
- Location of the first crack is the same in quasi-static as in fatigue loading
- This is the position with less favorable local fiber distribution (stress concentration, bad impregnation)
- This position is random
- Weibull transverse strength distribution

Weibull analysis in fatigue

90 layer = Chain of fragments

ΔL_1 ΔL_2 ΔL_3

Fragment: $\Delta L_i \Rightarrow 0$



n_σ

Defect (flaw) size distribution characterized by

n_σ number of flaws/length which would cause failure at stress σ

Probability of fragment failure $P_{fi} = n_\sigma \Delta L_i$

Weibull's proposal

$$n_\sigma L_0 = \left(\frac{\sigma}{\sigma_0}\right)^m$$

L_0 - reference length
m - Weibull shape parameter
σ_0 - scale parameter

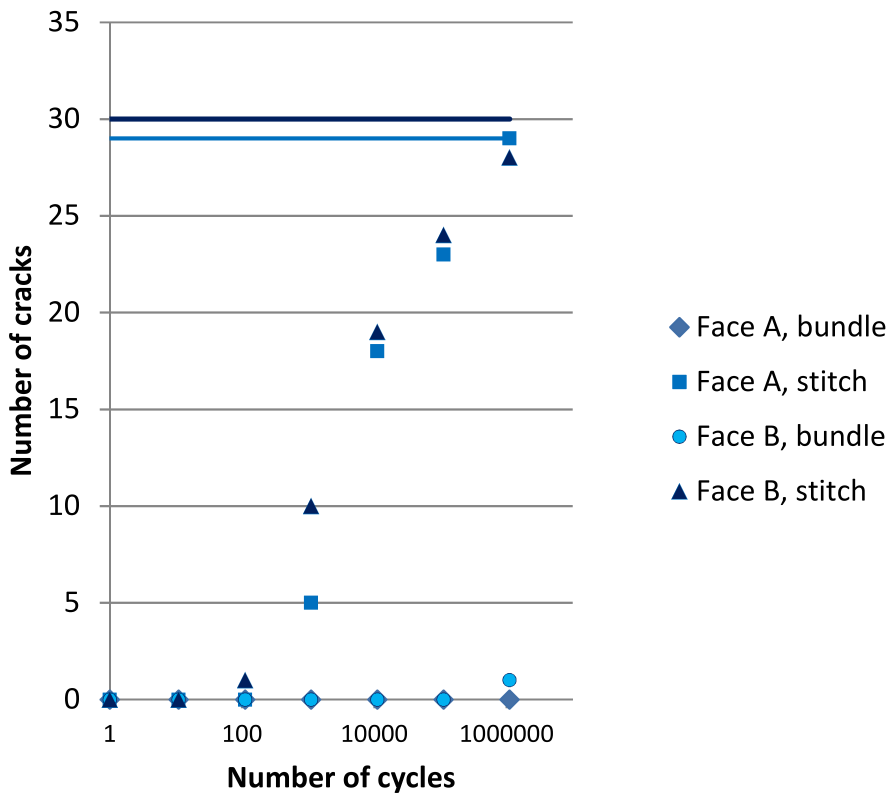
$$P_f = 1 - \exp\left(-\frac{L}{L_0}\left(\frac{\sigma}{\sigma_0}\right)^m\right)$$

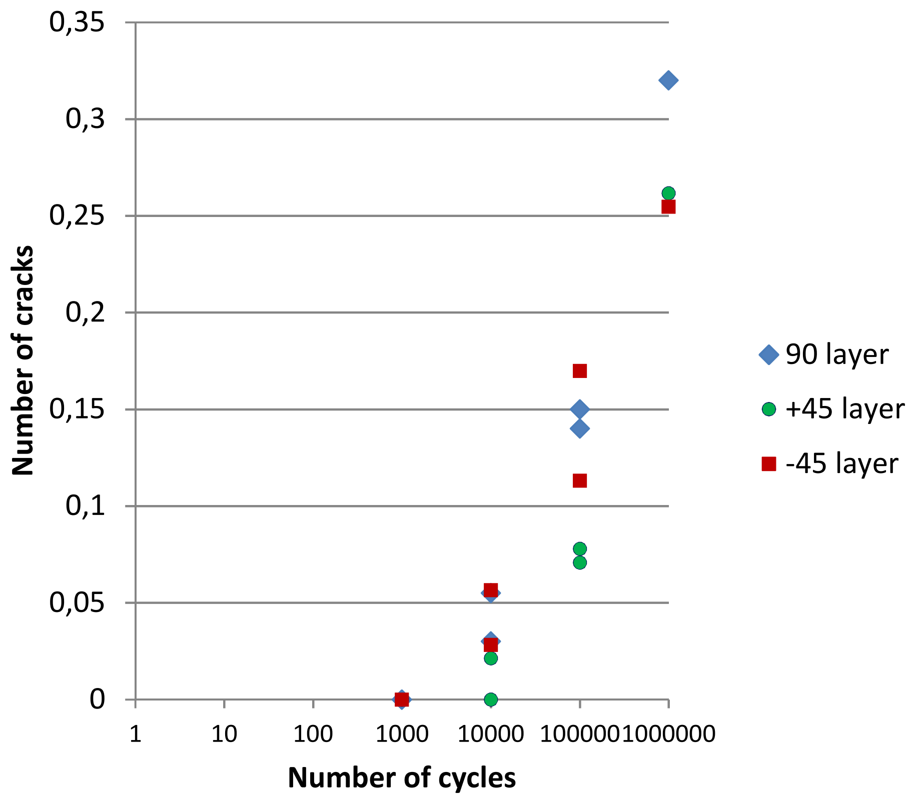
Ply strength

Suggestion:

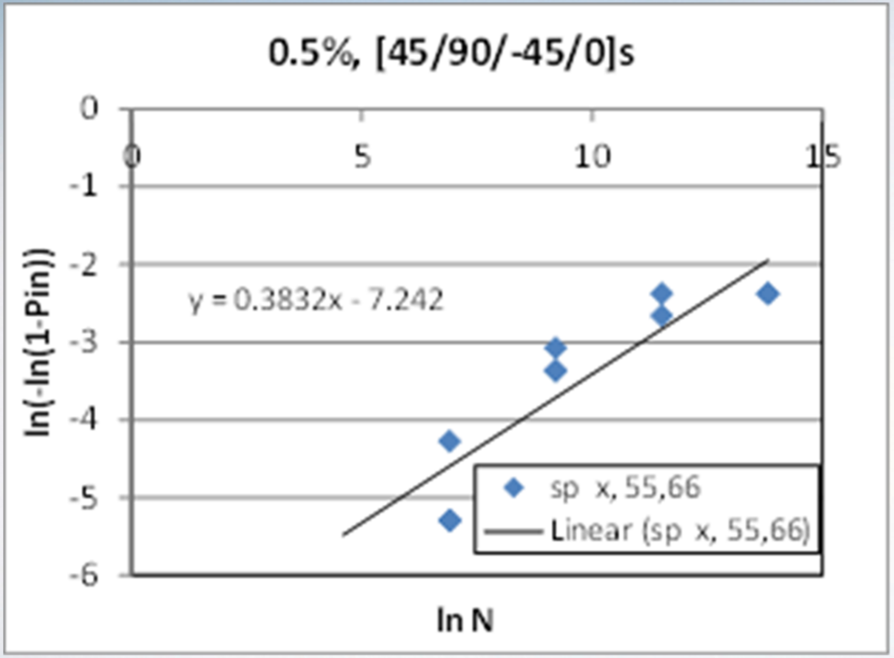
$$n_\sigma L_0 = N^n \left(\frac{\sigma}{\sigma_0}\right)^m \Rightarrow P_f = 1 - \exp\left(-\frac{L}{L_0} N^n \left(\frac{\sigma}{\sigma_0}\right)^m\right)$$

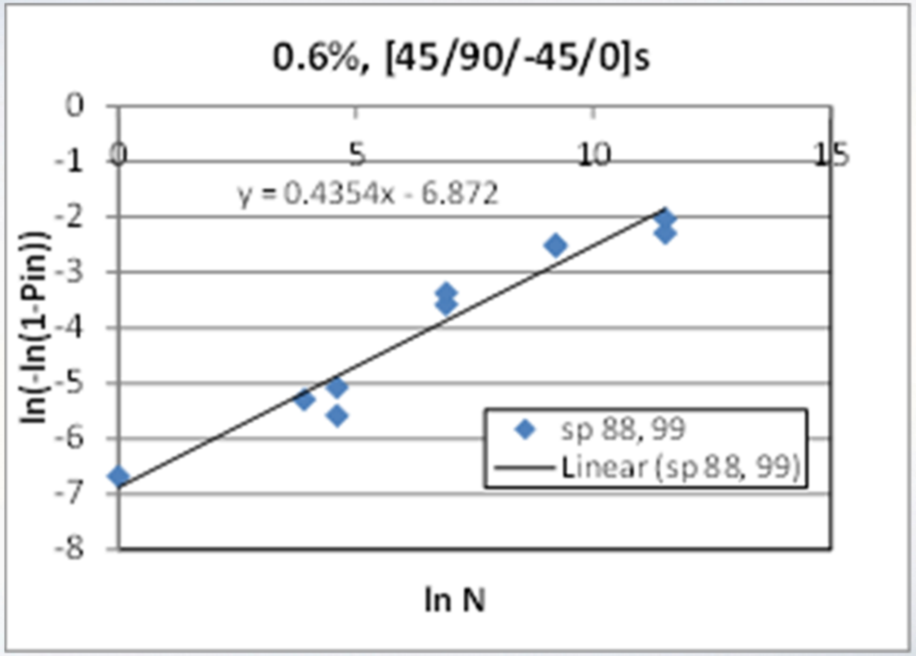
Damage development in fatigue





Weibull analysis in fatigue



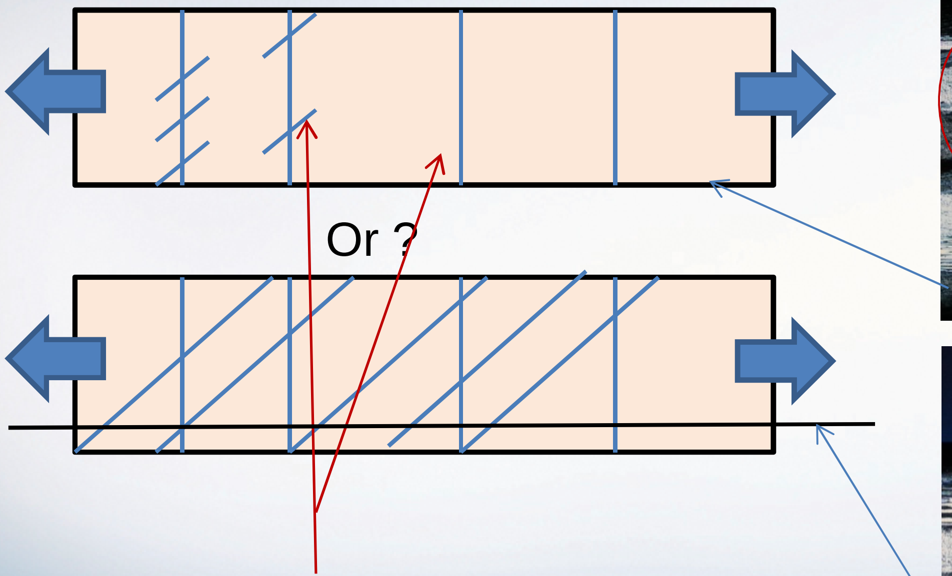


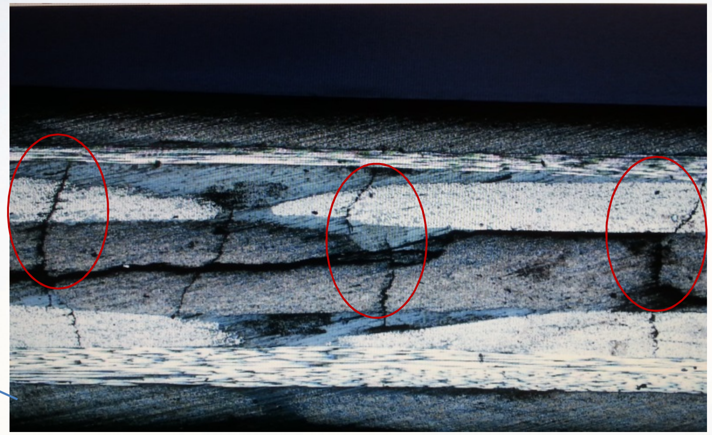
$$P_f = 1 - \exp\left(-\frac{L}{L_0} N^n \left(\frac{\sigma}{\sigma 0}\right)^m\right)$$

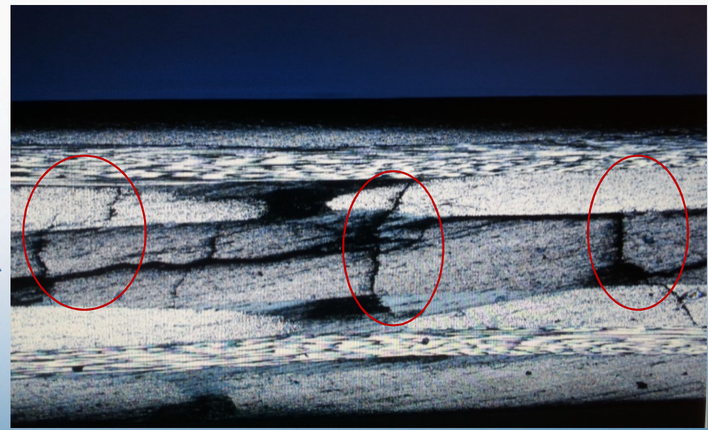
$$\ln(-\ln(1 - P_f)) = n \ln(N) + b$$

Cracks in 45-layers

Cyclic $N=10^6$, strain 0.4%







Cracks in 90 –layer
Cracks in 45-layer

Upper picture: specimen edge
Lower: inside the specimen (by polishing)

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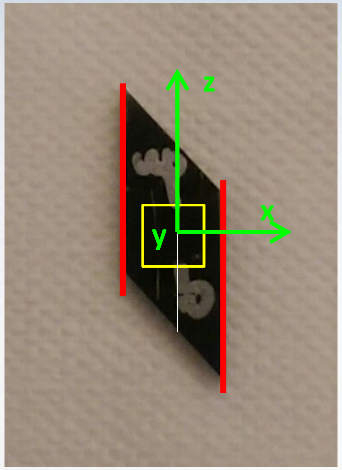
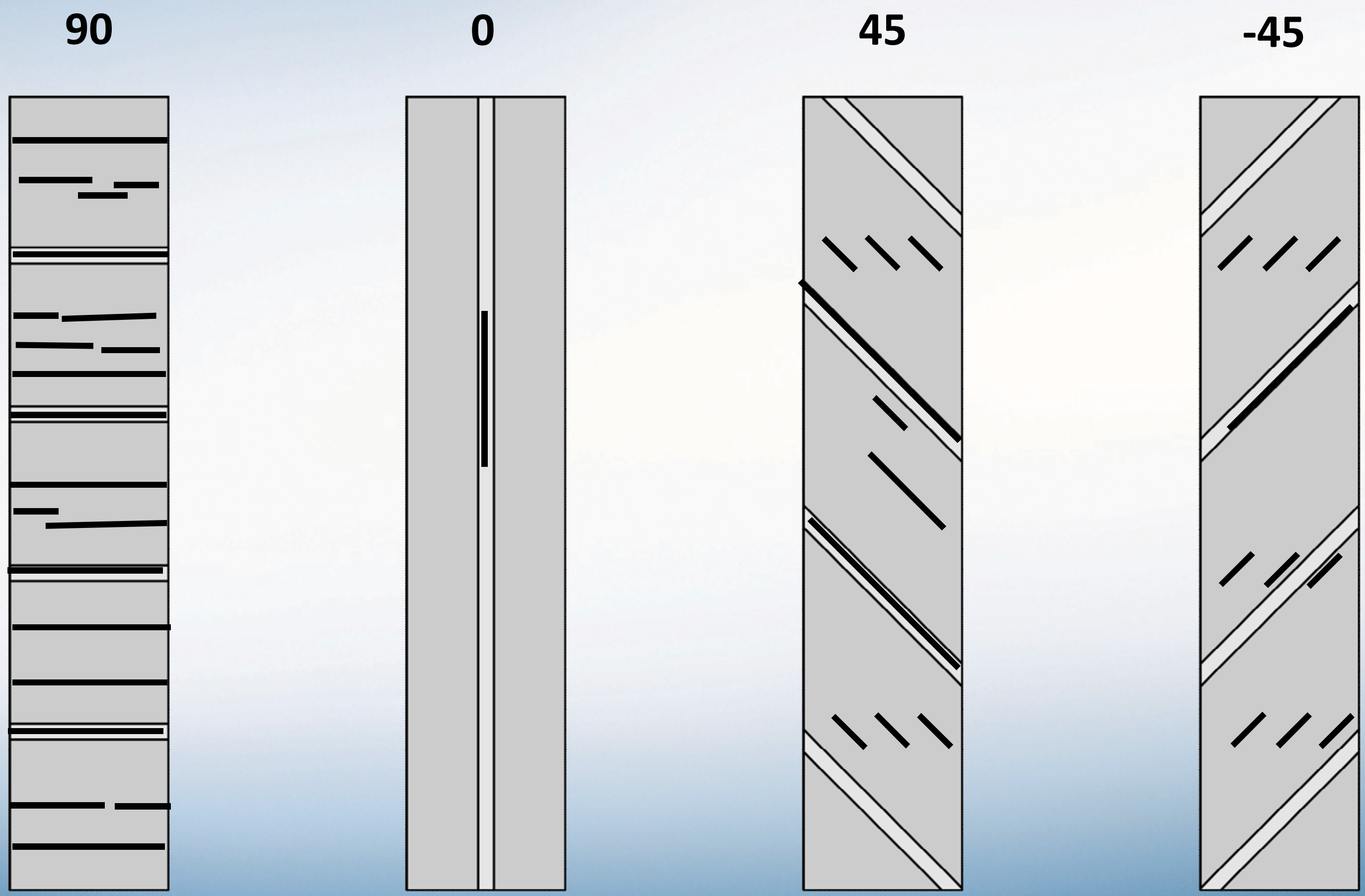
Damage inspection with micro CT



Original lay-up: [-45/90/45/0]s
yz view (edge view): [0/-45/90/45]s

Damage state in layers

Schematic vizualization, after 1 million load cycles at 0,5% strain



Conclusions

- Fatigue damage prediction tool has been developed based on Weibull analysis
- Methodology can potentially save significant time of fatigue testing
- Formation of transverse cracks in 45 layers is a complex mechanism
- Further tasks: Monte Carlo simulations, optimizing the form of Weibull based equation

Acknowledgement

- The presented work has been funded by VINNOVA within the NFFP program

Thank you for your attention!