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Failure Mechanisms in Composite Structures

D-STANDART Technical Workshop

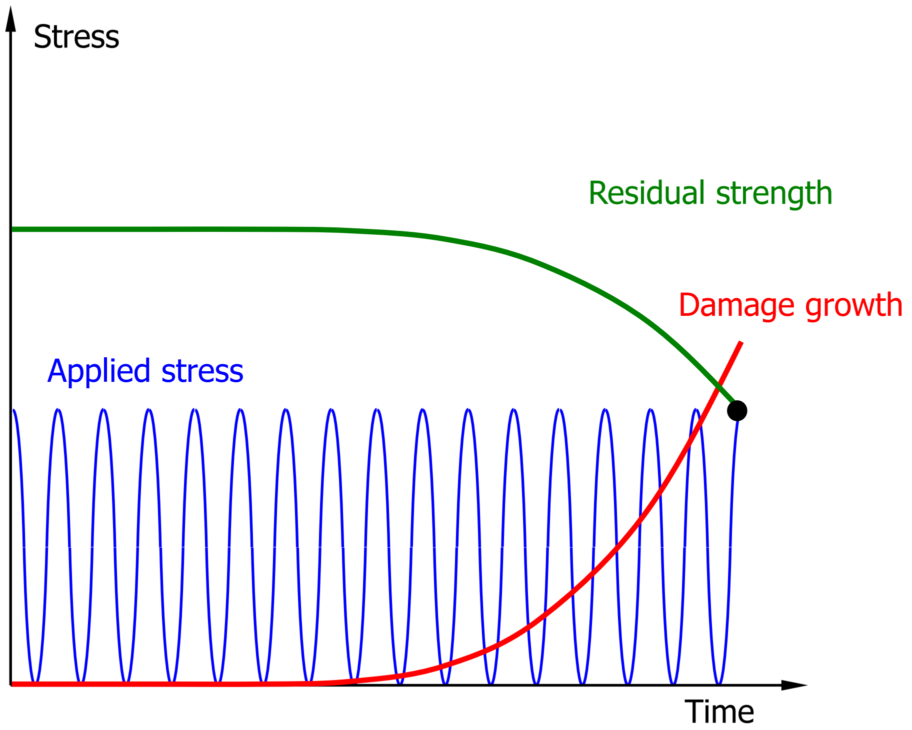
Delft, 8 of February 2024

J.A. Pascoe, F.M. Monticeli (TUD)

Funded by
the European Union

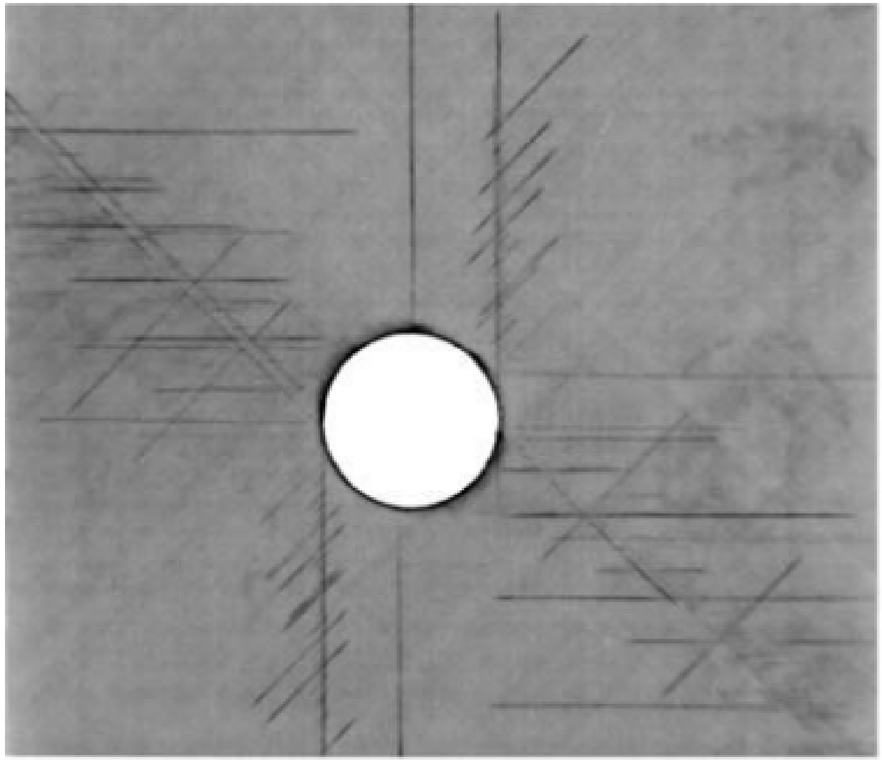
Fatigue in Composites - Definition

Fatigue in composites is the phenomenon/mechanism by which fluctuating (service) loads induce **permanent structural changes** through the **initiation and propagation of damages.** These changes include a loss of material stiffness and/or load carrying capability which may lead to **structural failure below the monotonic failure stress.**

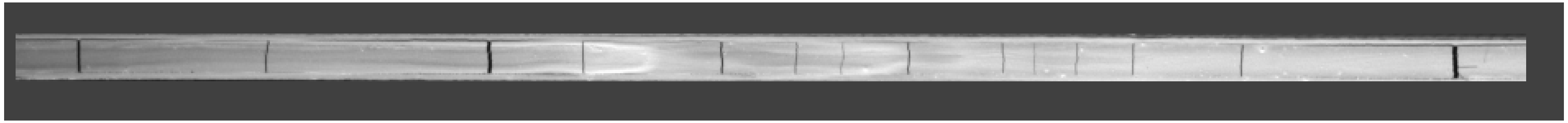


Taxonomy

- What breaks?
  - Matrix



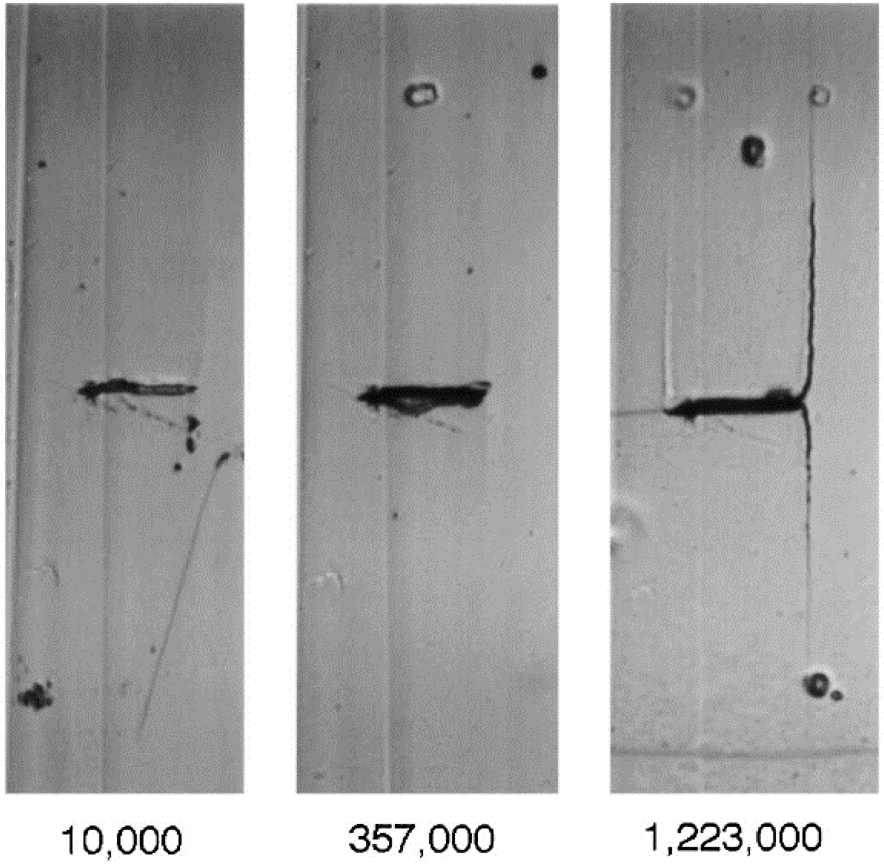
Hallett et al (2009)



Thesis Xi Li, (2022), TU Delft

Taxonomy

- What breaks?
  - Matrix
  - Fibres
  - Fibre-Matrix interface



Gamstedt & Talreja (1999)

Taxonomy

- What breaks?
  - Matrix
  - Fibres
  - Fibre-Matrix interface

- What type of thing breaks?
  - Constituent
    - Matrix cracking (transverse, splitting)
    - Fibre fracture
    - Core failure (sandwich)
  - Interface
    - Fibre-matrix disbonding
    - Delamination

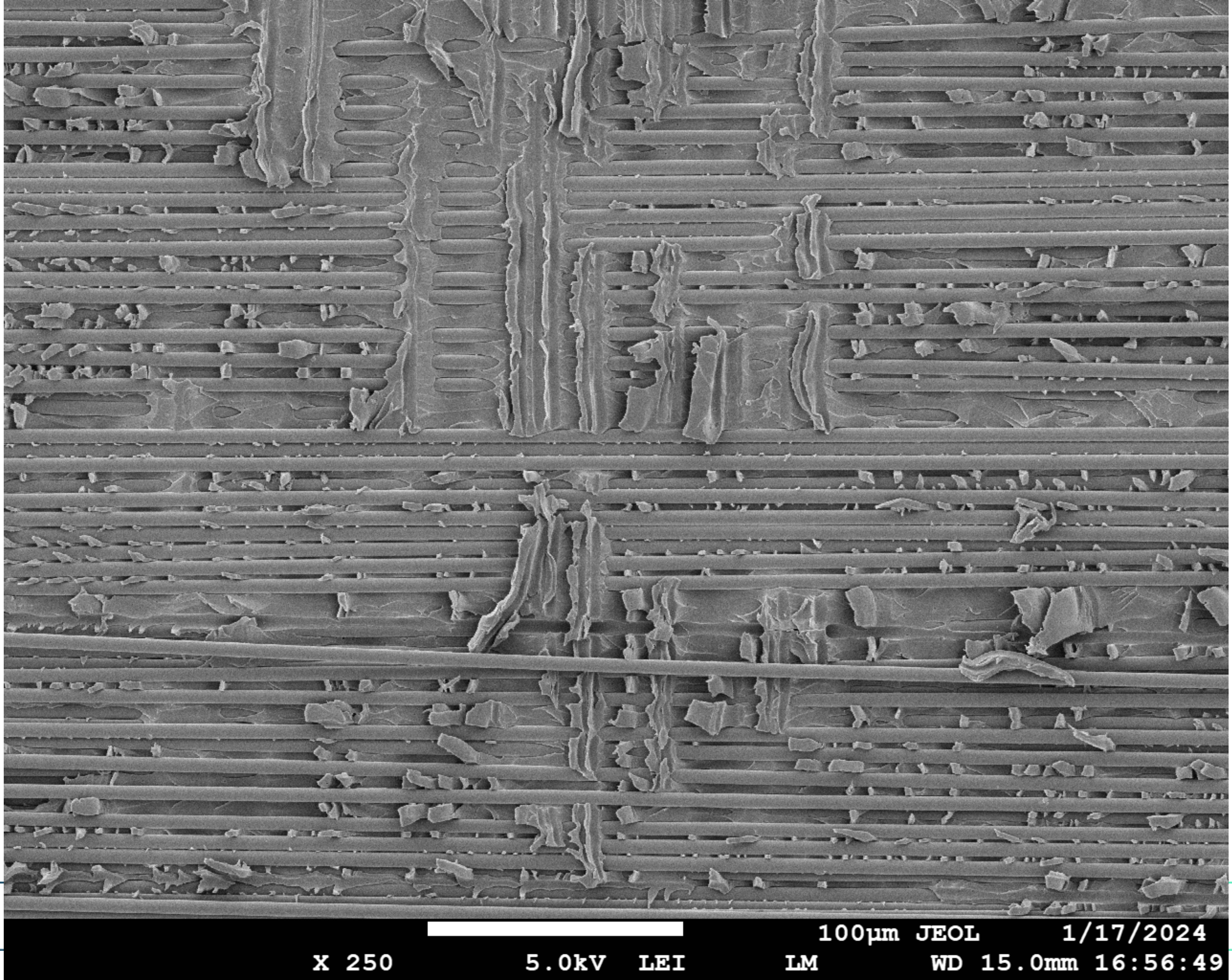


Image: Wenjie Tu

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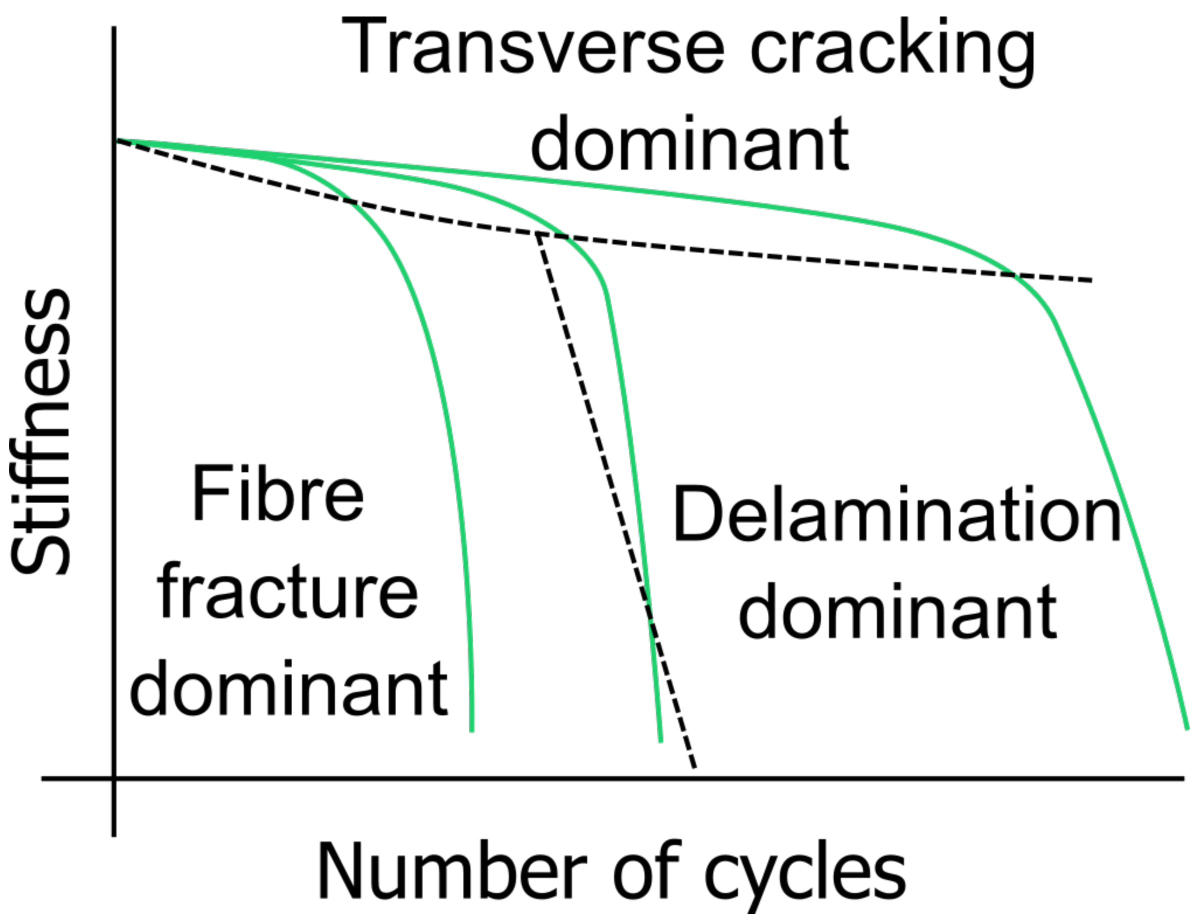
Damage Evolution

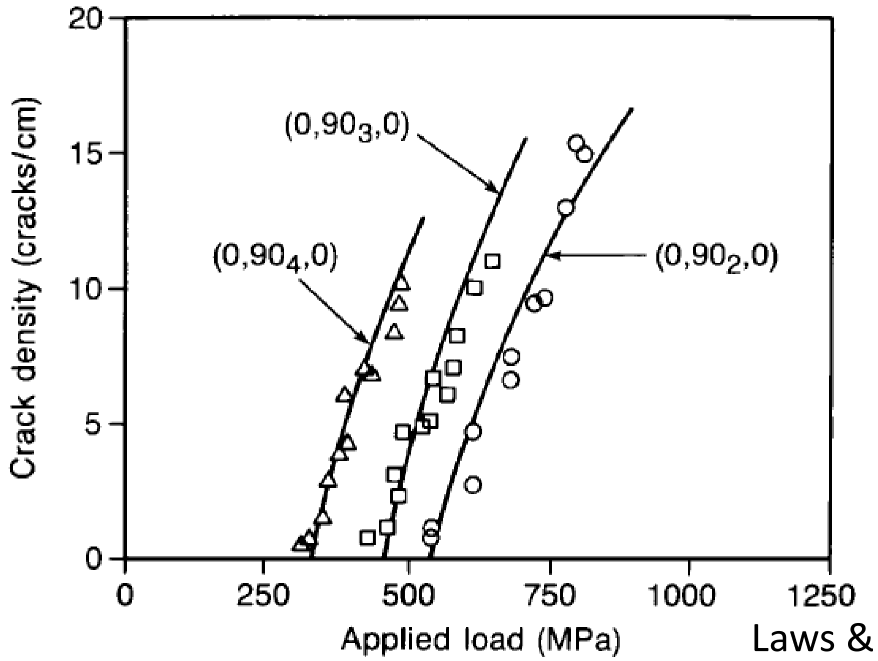
- Multiple damage modes occur simultaneously
- Dominant damage mode varies with stress and life
- High cycle fatigue
  - Matrix cracking
  - Delamination growth



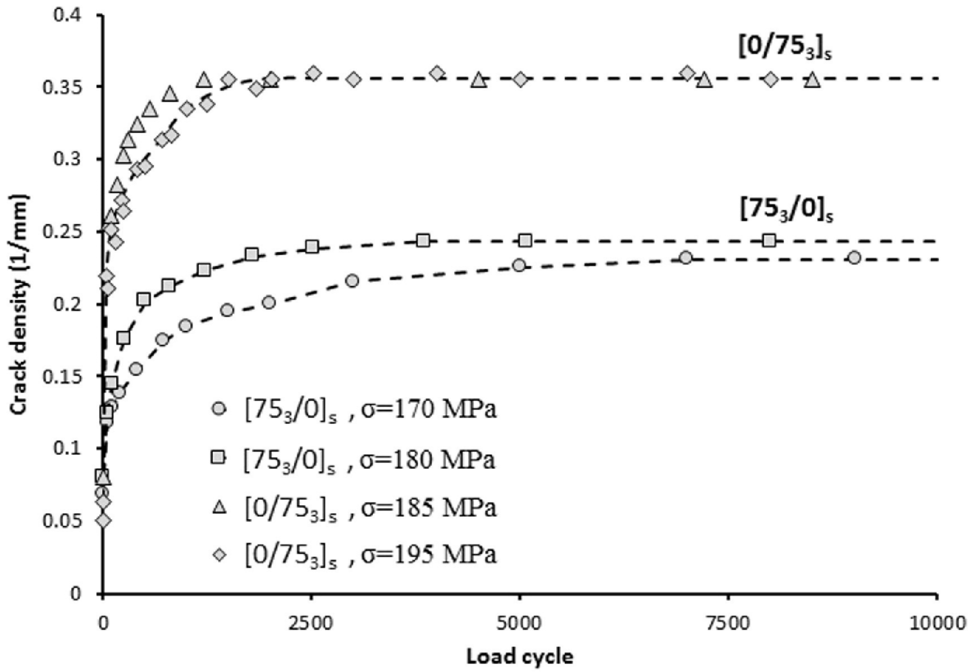
Damage Mechanisms in Detail

Matrix Crack Density

- Crack density is a function of:
  - Ply group thickness (thicker transverse ply group causes earlier crack initiation)
  - Stress level
  - Fibre orientations in adjacent plies



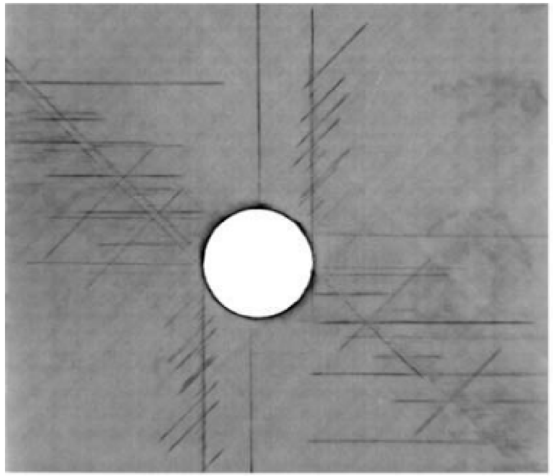
Laws & Dvorak, 1998



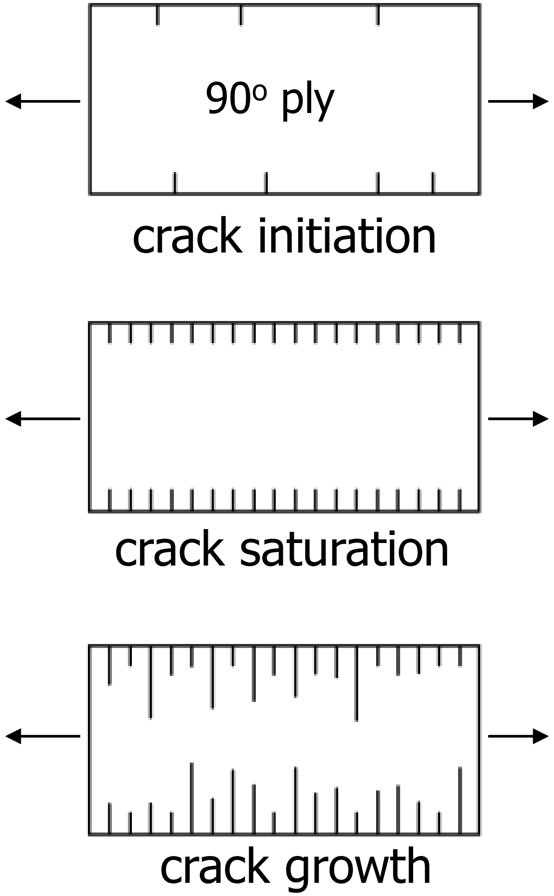
Mohammadi & Pakdel, 2018

Matrix Crack Damage Progression

- In regions of uniform stress
  - Crack initiation at free surfaces (lower energy)
  - Saturation of matrix cracks
  - Crack growth
- Uniform material degradation
- Localized growth/degradation possible at stress risers (notches, etc.)

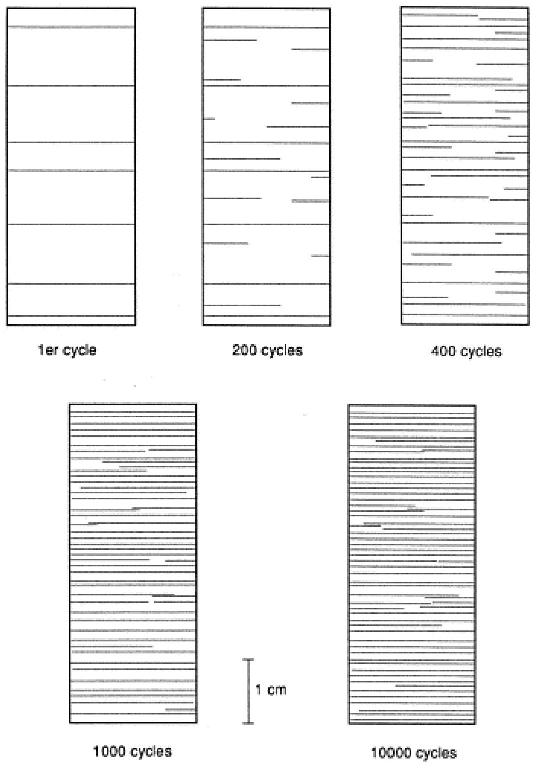


Hallett et al (2009)



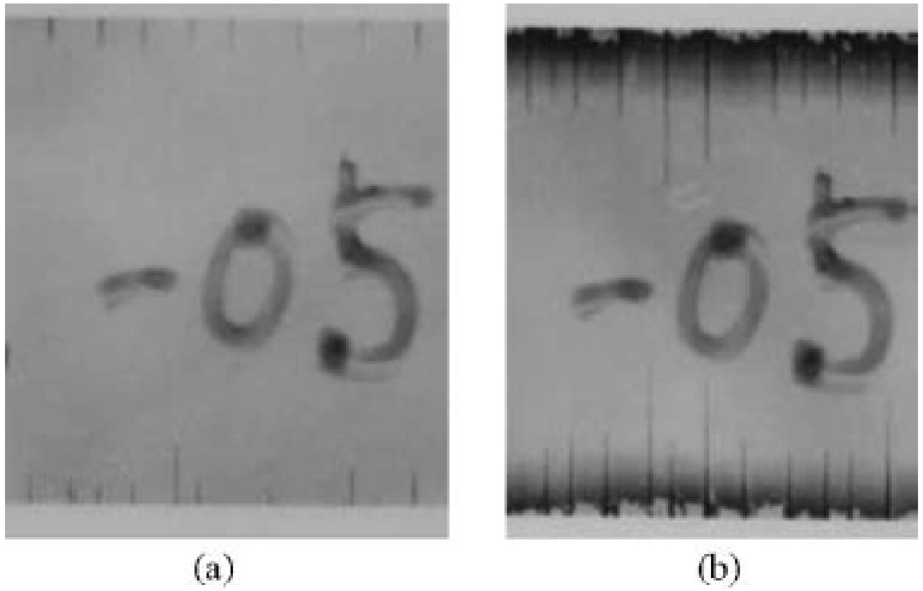
Matrix Crack Damage Progression

Instant through-width growth



Berthelot et al. (2001)

Saturation



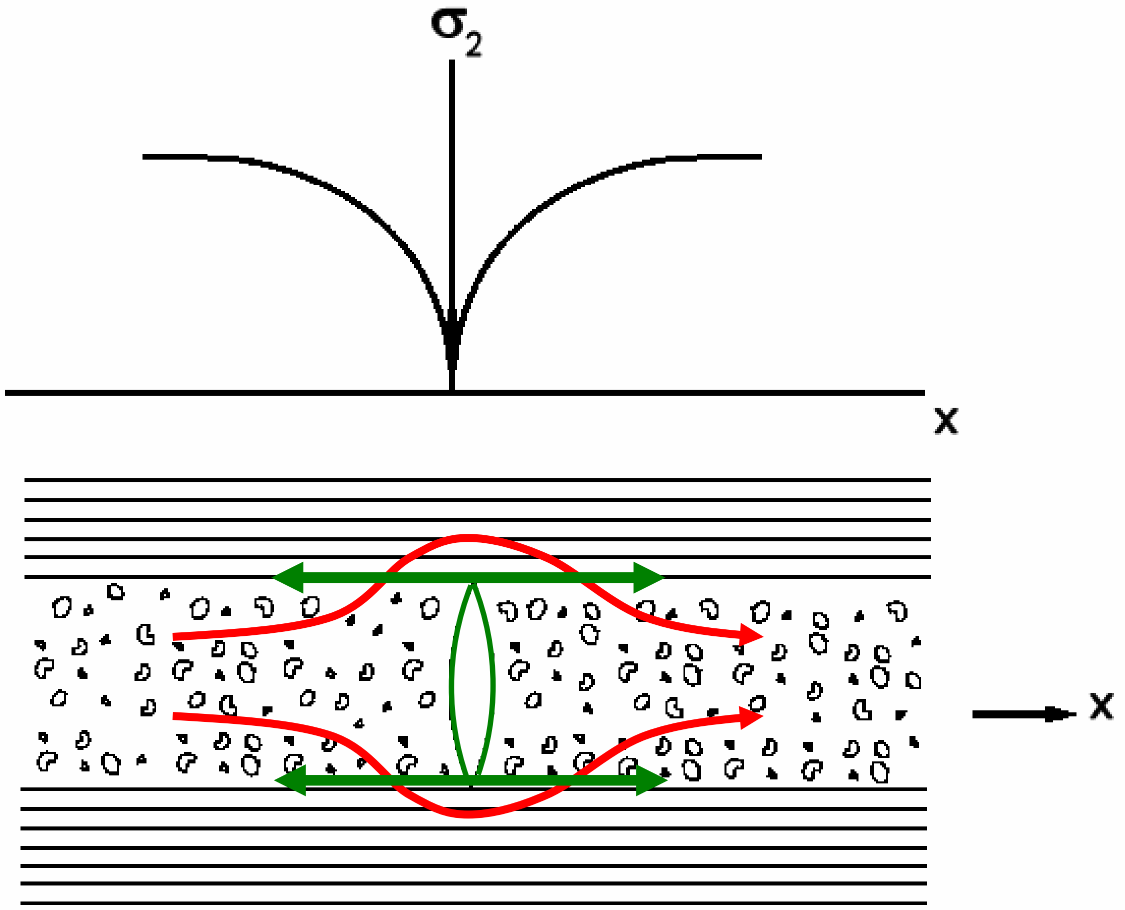
N = 3000 cycles

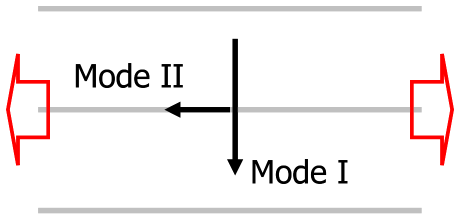
N = 10 000 cycles

Yokozeki et al. (2002)

Matrix Crack Penetration/Deflection

- Matrix crack interrupts load path in cracked ply
- Redistribution of load
- Penetration/deflection of crack determined by energy release rate





$$\frac{G_{II}}{G_{IIc}} \; vs \; \frac{G_I}{G_{Ic}}$$

Matrix Crack Penetration/Deflection

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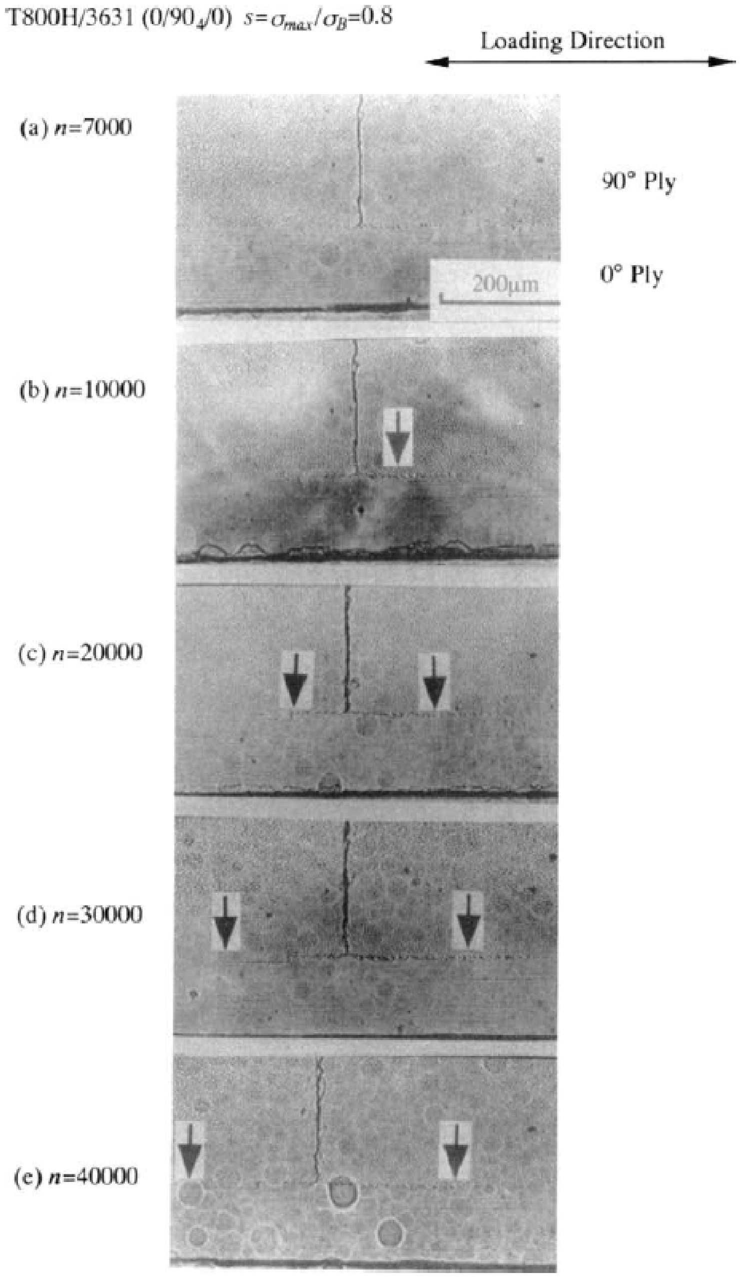
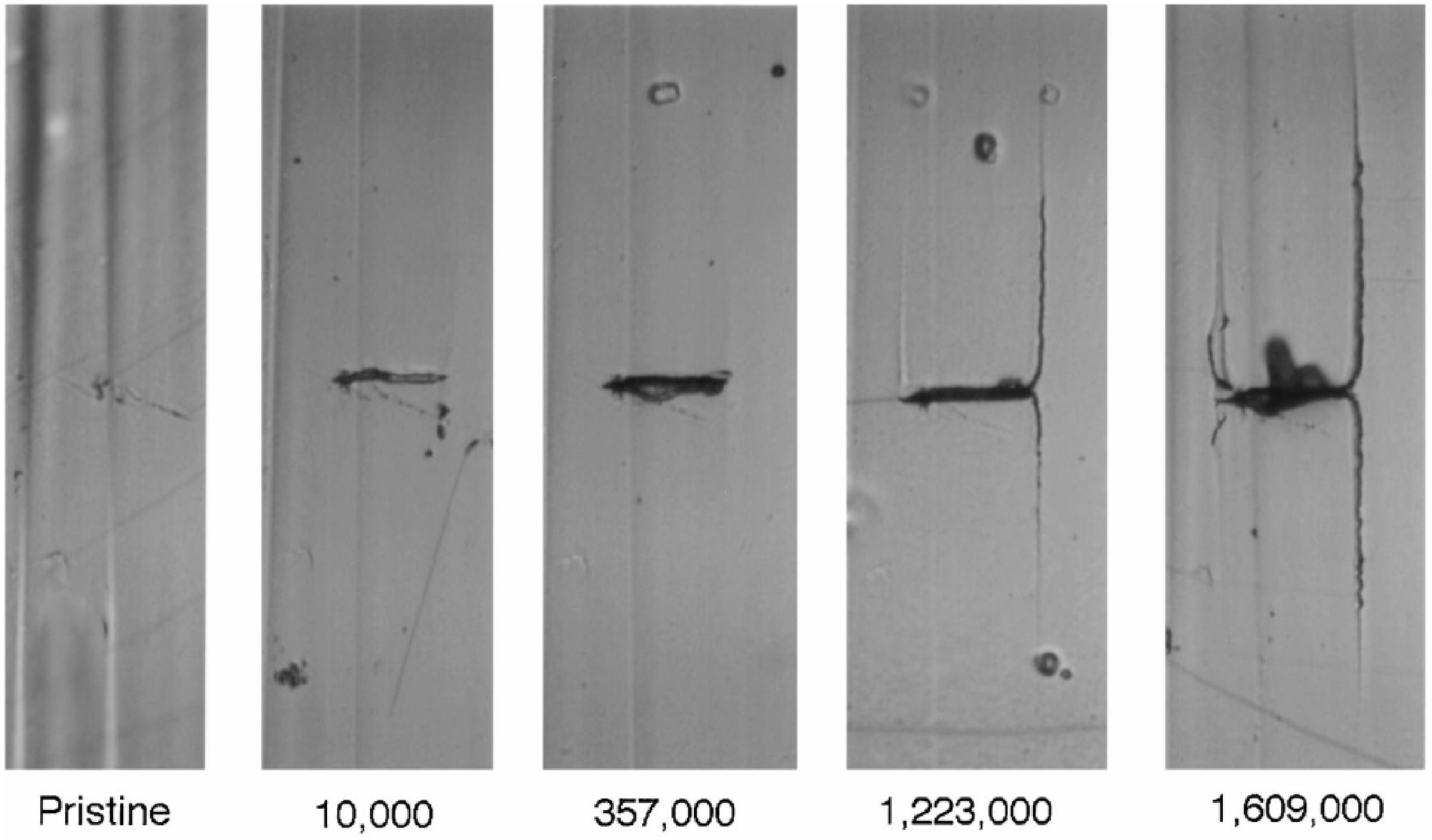


Figure 3 Delamination growth from a tip of a transverse crack in T800H/3631 [0/90$_4$/0] laminate, s = 0.80: (a) n = 7000; (b) n = 10 000; (c) n = 20 000; (d) n = 30 000; (e) n = 40 000

Takeda et al. (1995)

Fibre fracture – matrix crack interaction



Stress redistribution around crack

Damage initiation and growth in matrix

JOURNAL OF MATERIALS SCIENCE 34 (1999) 2535–2546 Gamstedt & Talreja

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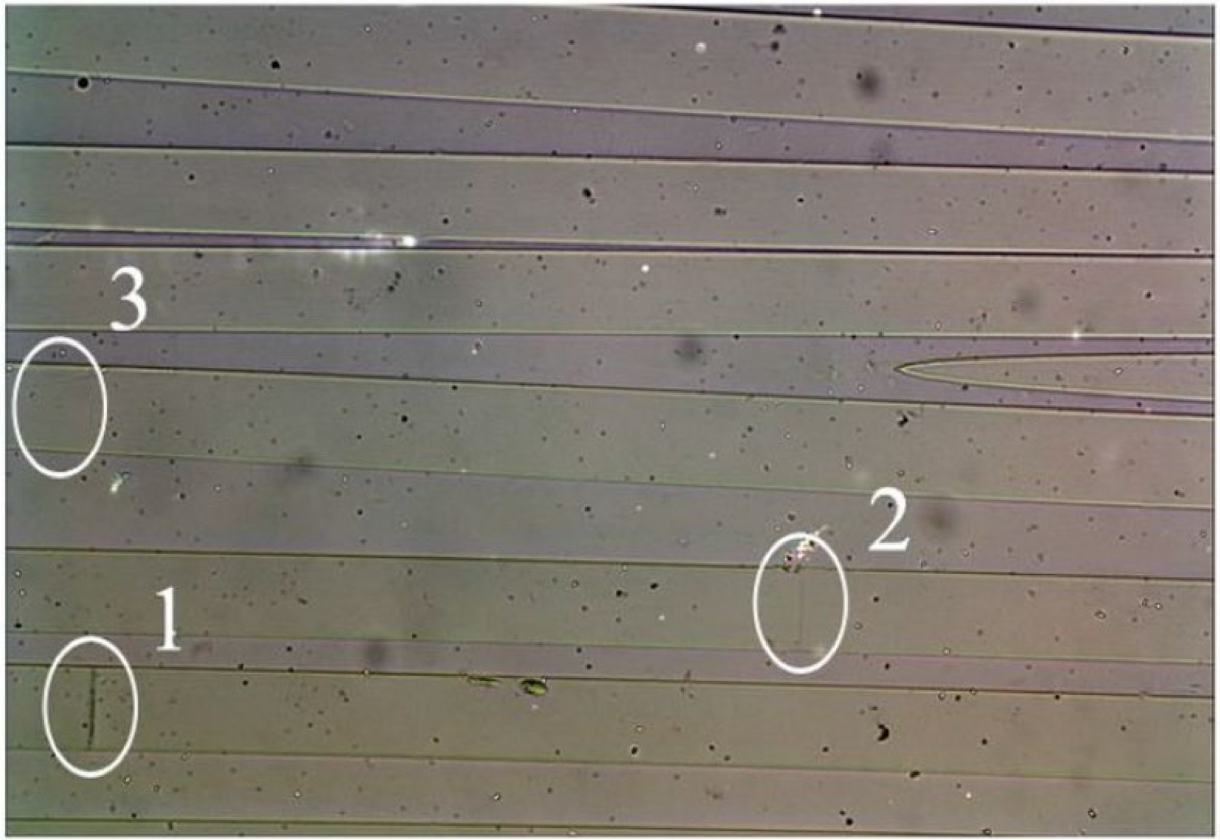
Fibre failure



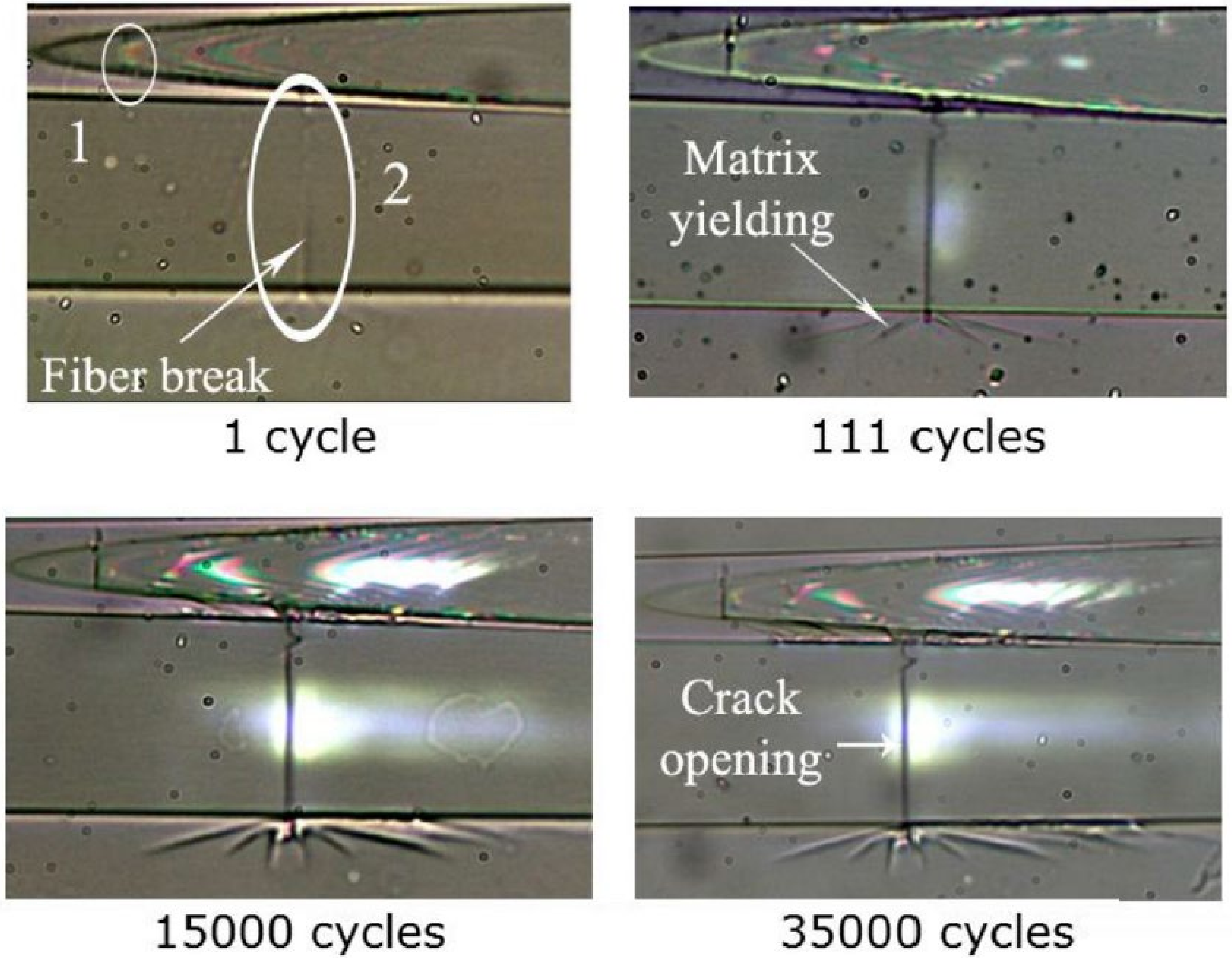
1 cycle

Fibre failure starts in 1st cycle

Fibre strength is stochastic

O. Castro et al.

Polymer Testing 74 (2019) 216–224

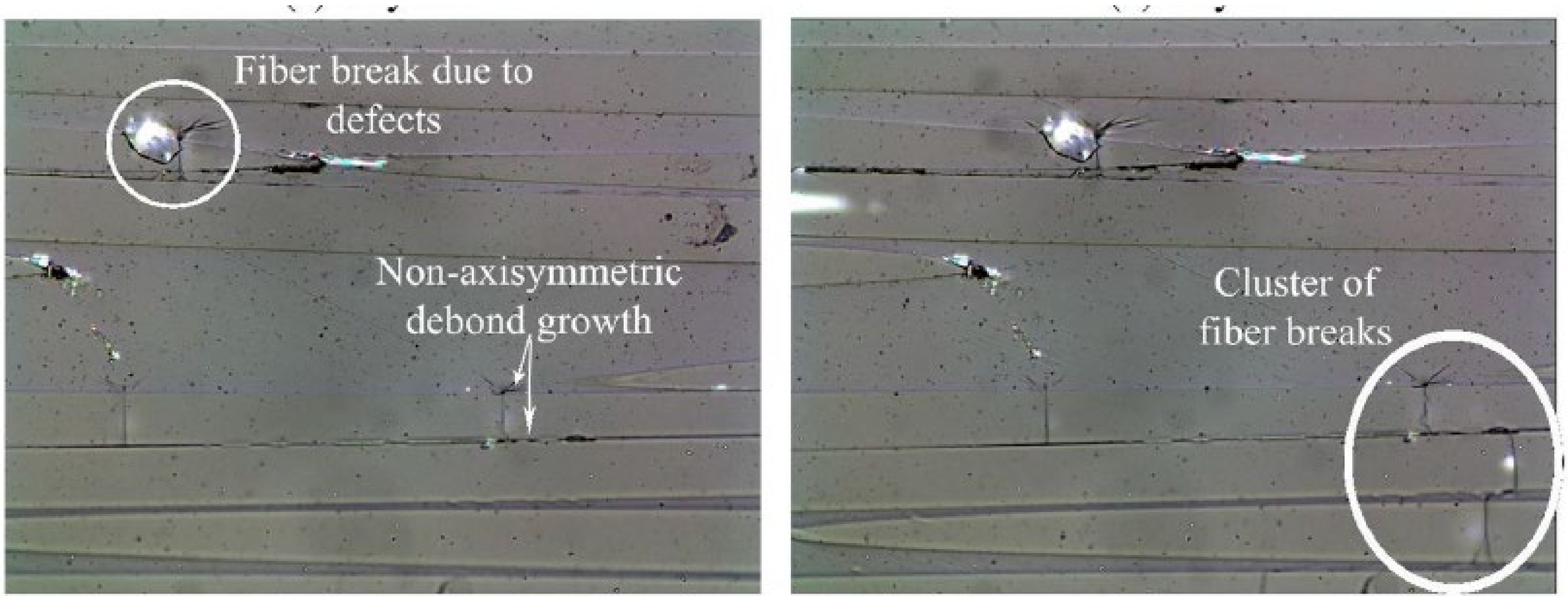


O. Castro et al.

Polymer Testing 74 (2019) 216–224

Stress redistribution around crack

Damage initiation and growth in matrix



(c) 1000 cycles (d) 6076 cycles

O. Castro et al.

Polymer Testing 74 (2019) 216–224

Initiation of new fibre damage

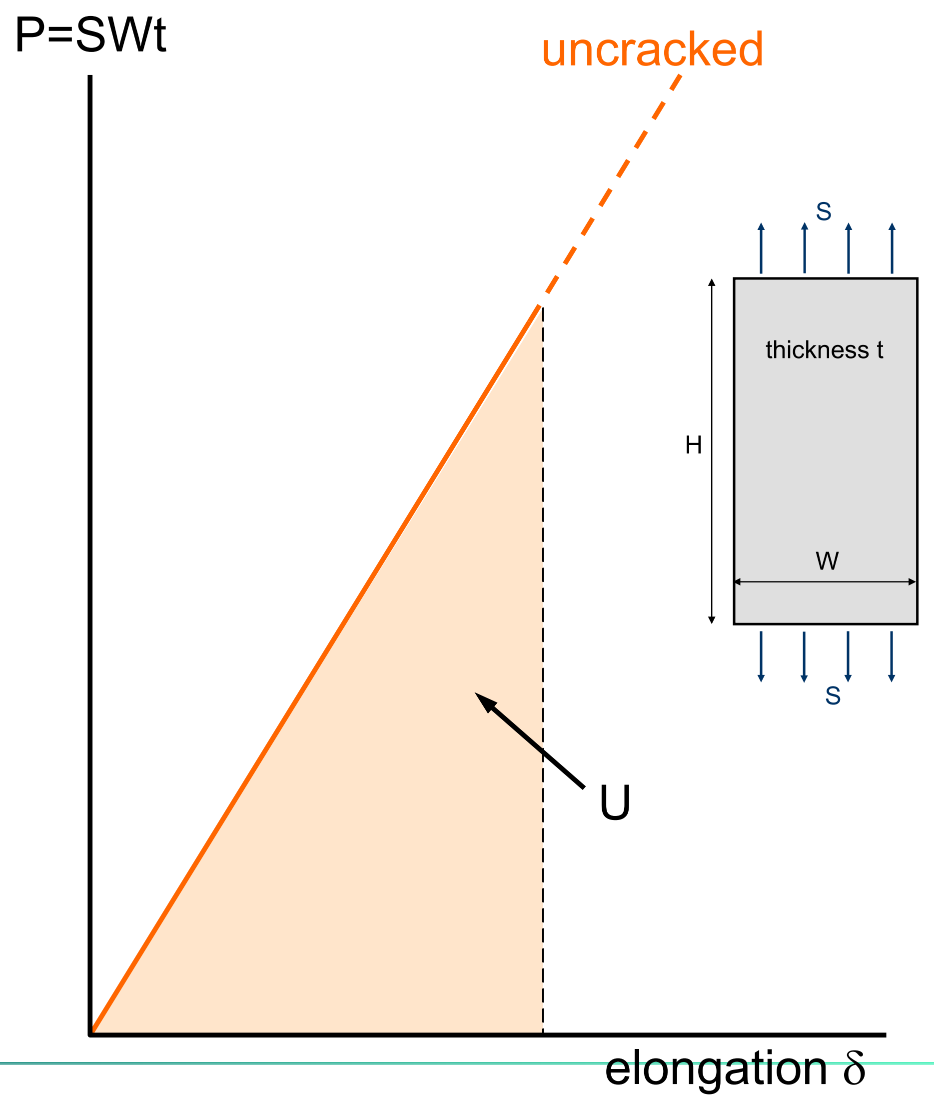
Strain energy release rates - cracks

- Load: P = S (Wt)
- Elongation: $\delta = (S/E)H$

- Elastic energy (potential energy):

$$U = \frac{1}{2}P\delta = \frac{1}{2}\cdot SWt\cdot\frac{S}{E}H = \frac{1}{2}\frac{S^2}{E}\cdot HWt$$

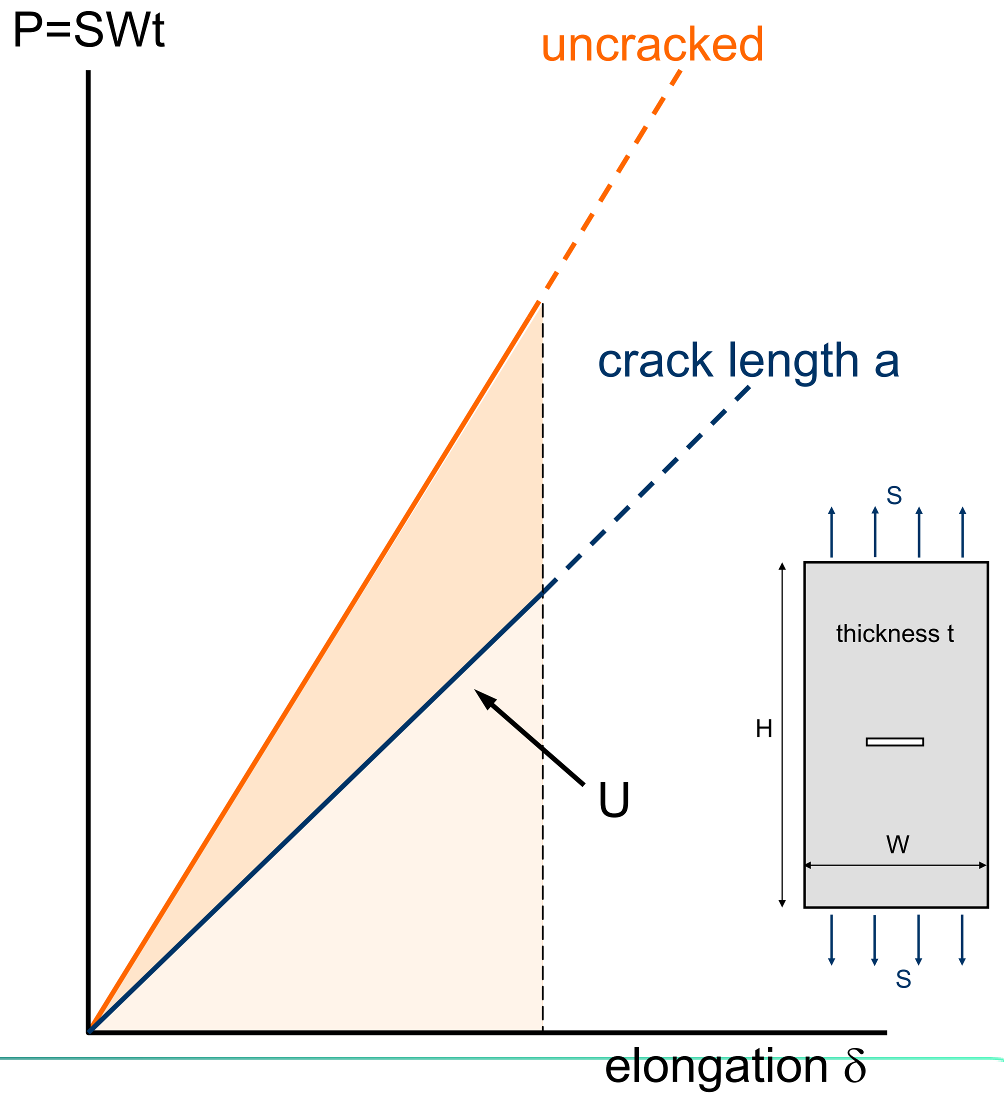
- HWt = plate volume
- $\frac{1}{2}S^2/E$ = strain energy density (strain energy per unit volume)



Strain energy release rates - cracks

- Lower stiffness
- Less energy will be stored in plate at same elongation

$\Rightarrow$ Elastic strain energy relaxation



Strain energy release rates - cracks

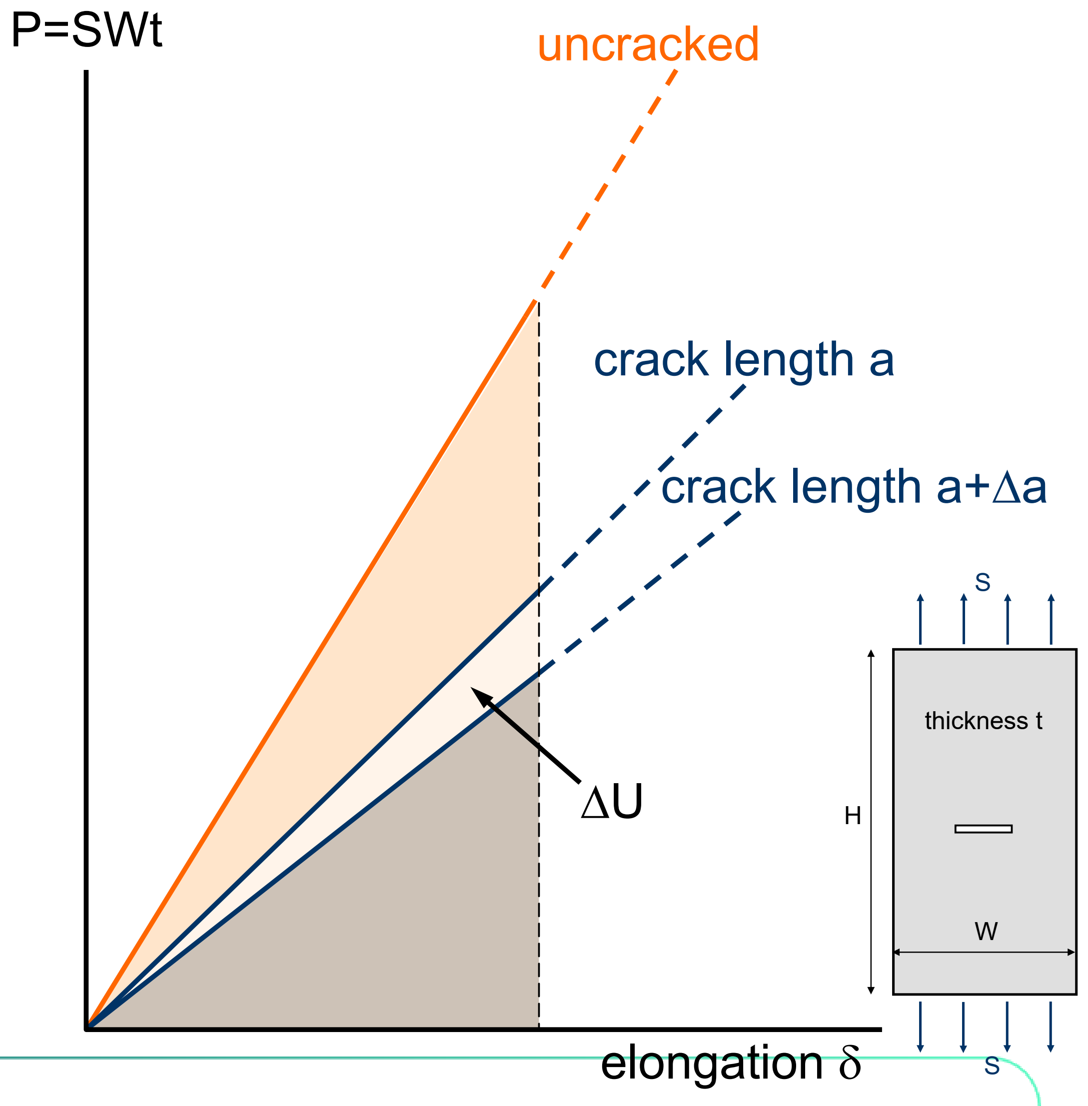
- Small reduction in stiffness
- Small relaxation of elastic strain energy ΔU at same elongation

$$\Delta U = \frac{K^2}{E*} \Delta a$$

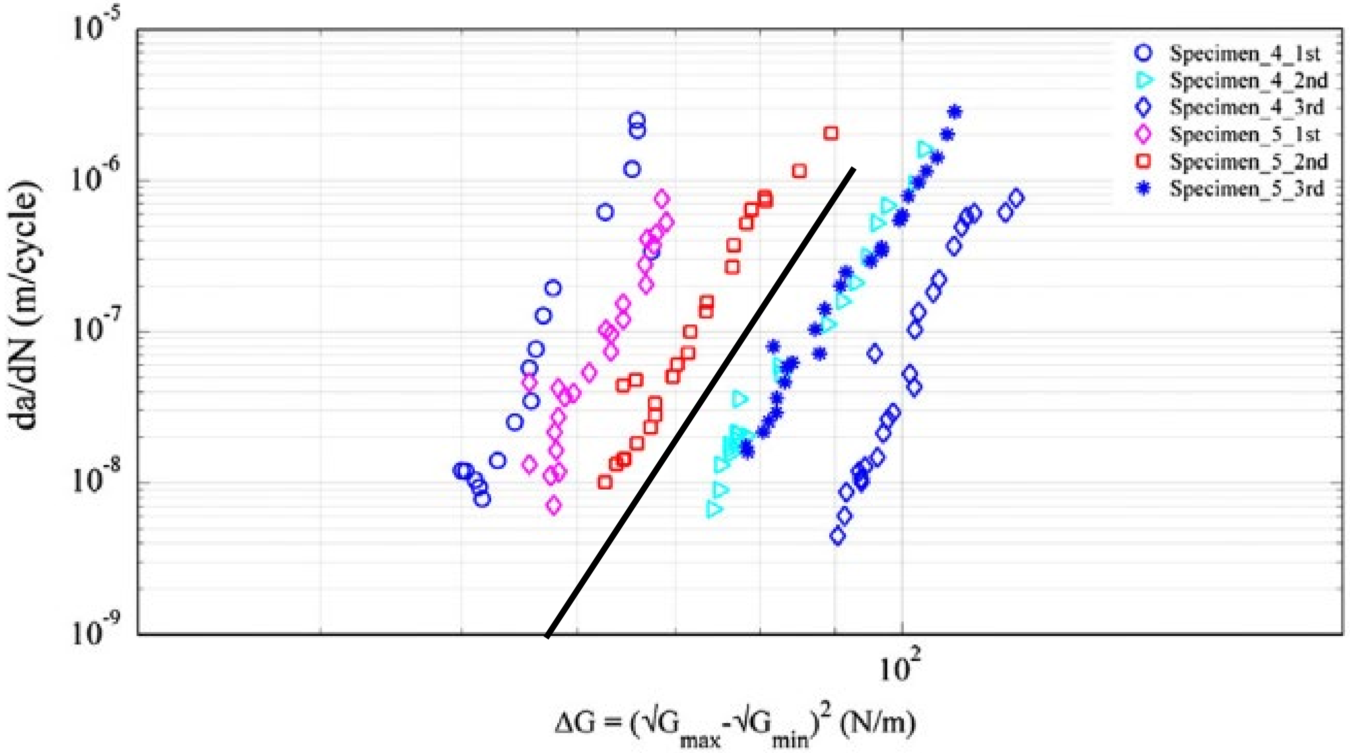
$E^* = E$ (plane stress)
$E^* = E/(1-\nu^2)$ (plane strain)

- "Crack driving force"

$$G = \frac{dU}{da} = \frac{K^2}{E^*}$$



Predicting Delamination Growth



Yao et al. (2016)

Calculate analytically or with FE

$$G = f(load, delamination\ length)$$

$$\frac{da}{dN} = CG_{max}^n \text{ or } C\Delta\sqrt{G}^n \text{ or } C\Delta G^n$$

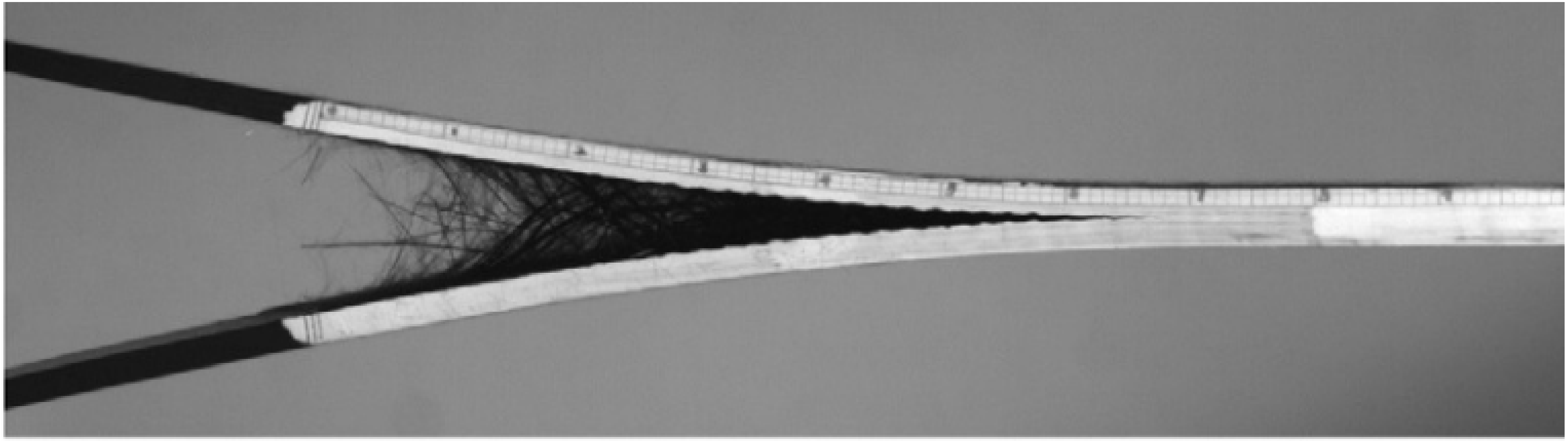
$$\Delta a = \frac{da}{dN}\Delta N$$

$$a = a_0 + \sum \Delta a_i$$

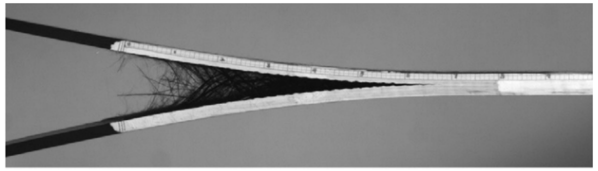
Iterate to generate *a* vs *N* curve

Fibre Bridging

L. Yao et al. / Composites: Part A 63 (2014) 103–109



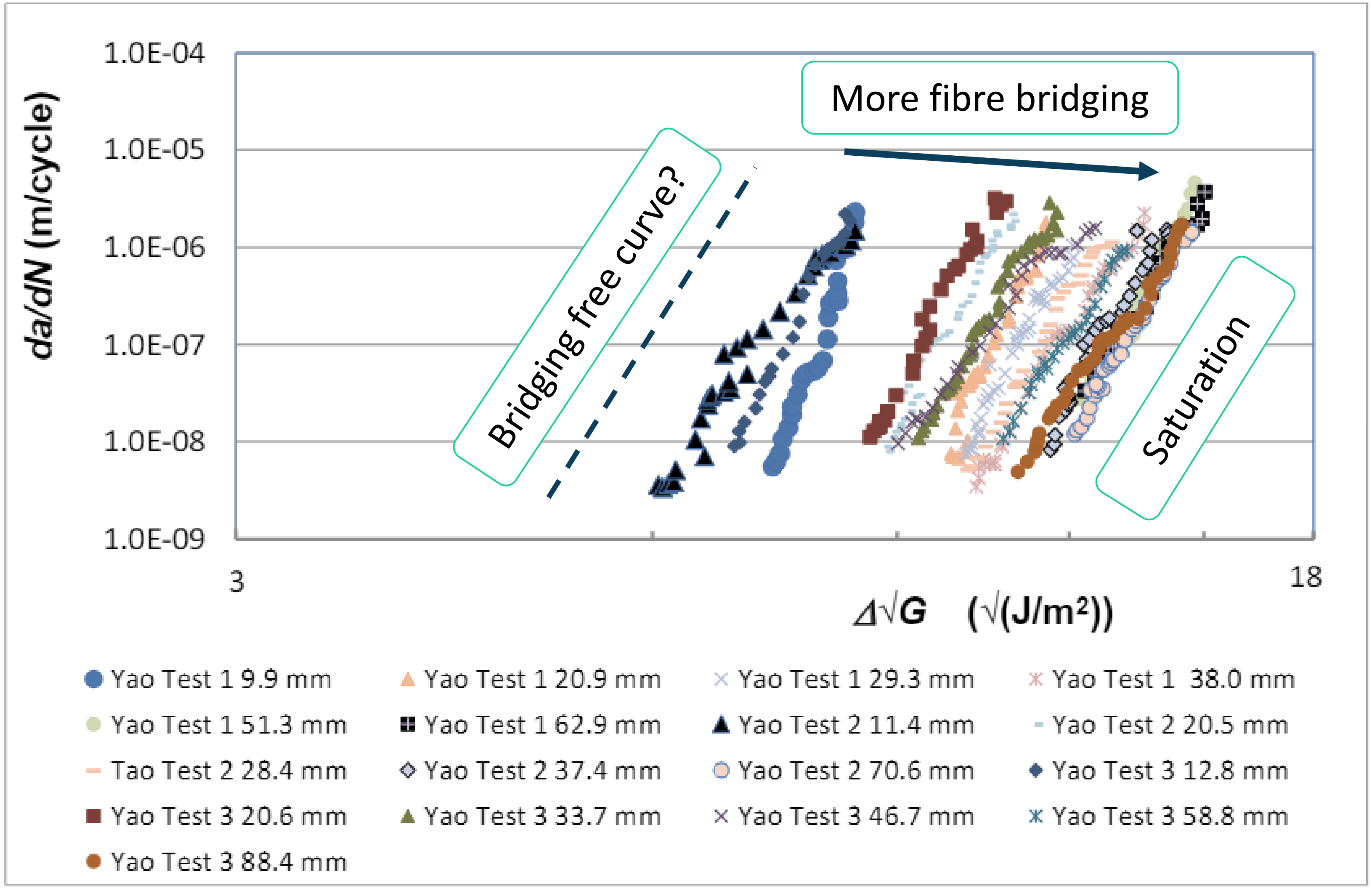
L. Yao et al. / Composites: Part A 63 (2014) 103–109



How to deal with this?

Possible to reconstruct 'bridging free' curve as worst case?

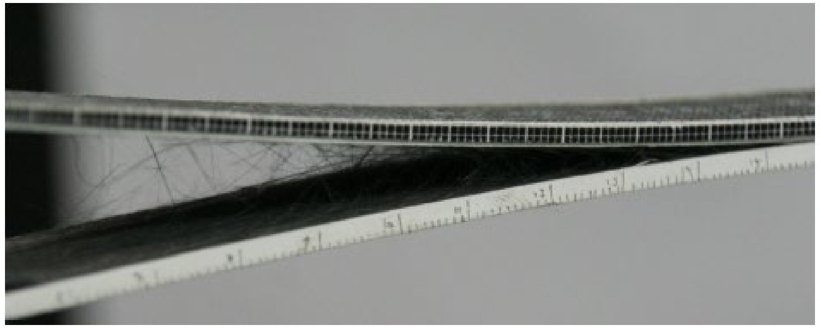
Rhys Jones et al. / Procedia Structural Integrity 28 (2020) 26–38 31



Effect of fibre orientation

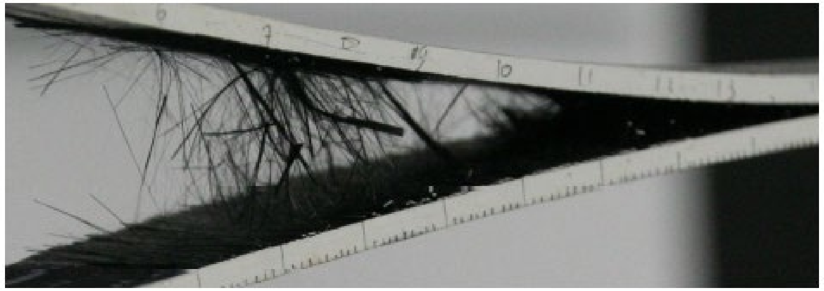
Prior results at TUD

0//0



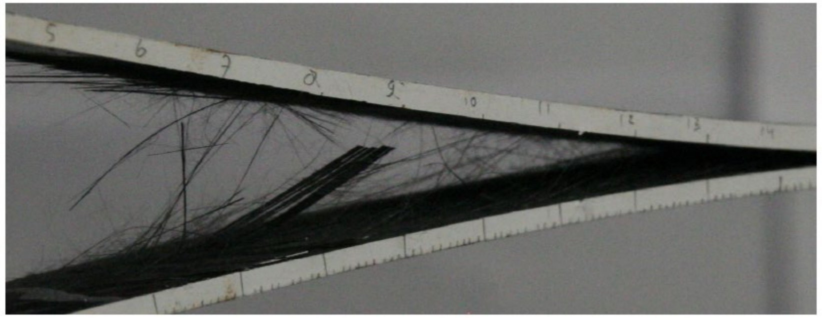
"Classical" fibre bridging

0//90



Oscillatory migration

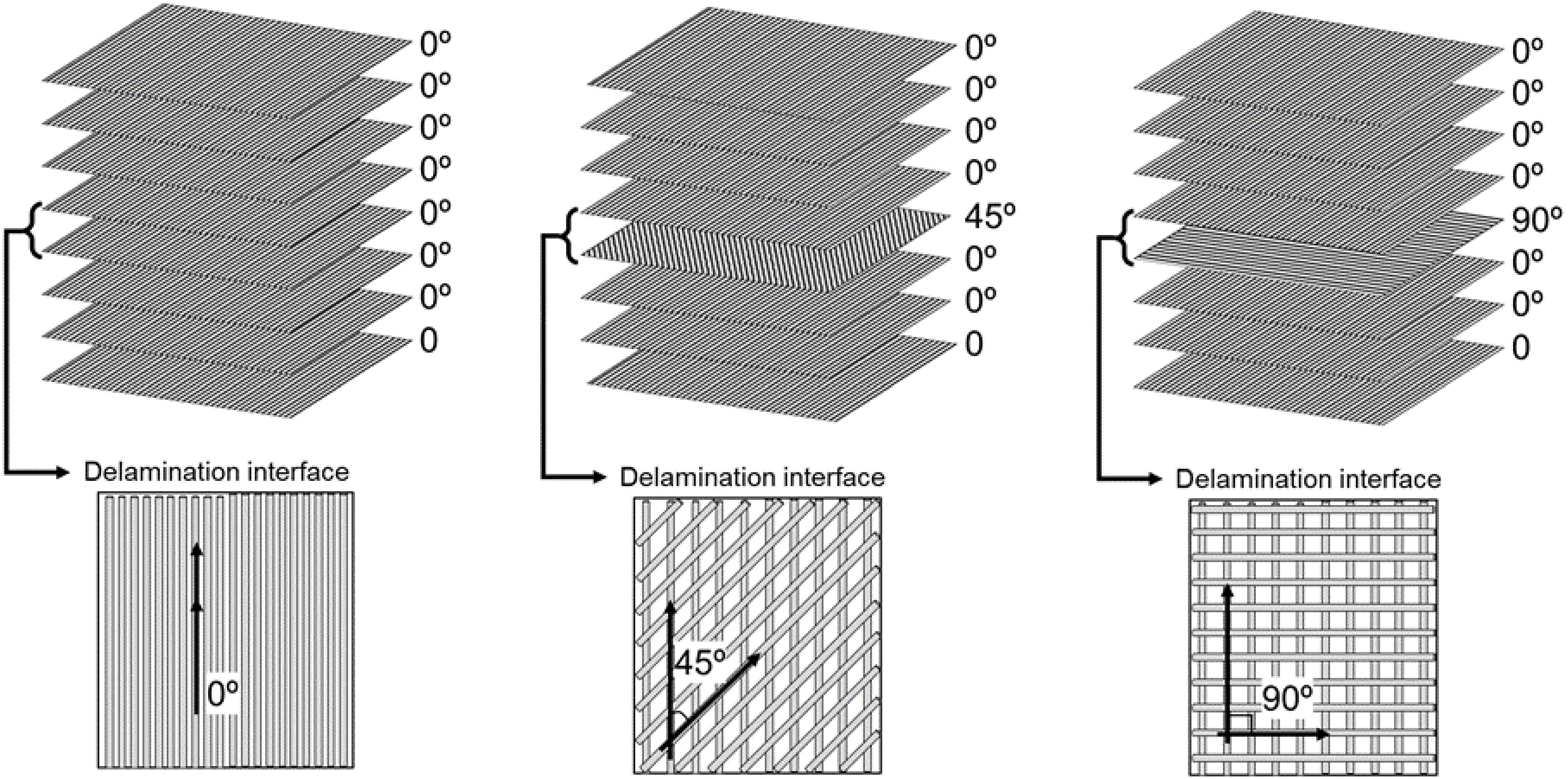
0//45



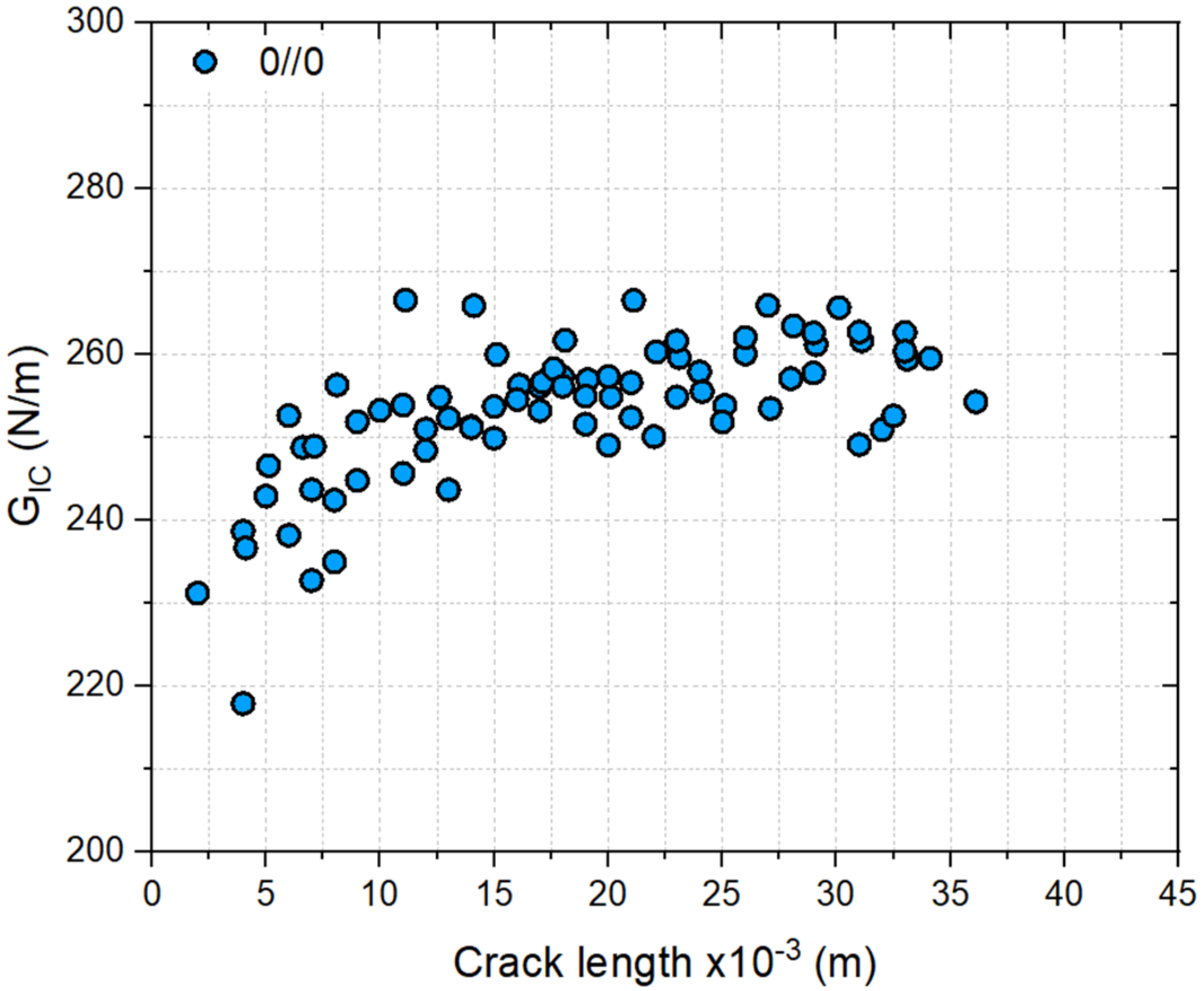
Bundle pull-out

Fibre orientation effect

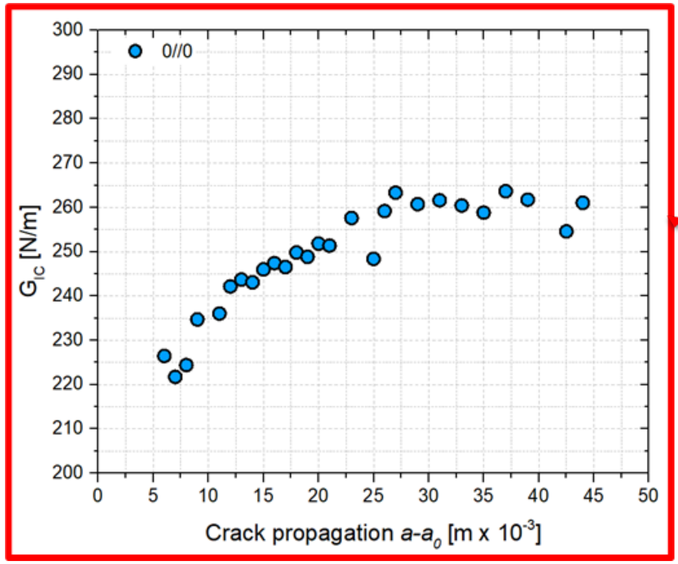
Stacking sequence (Fiber orientation)

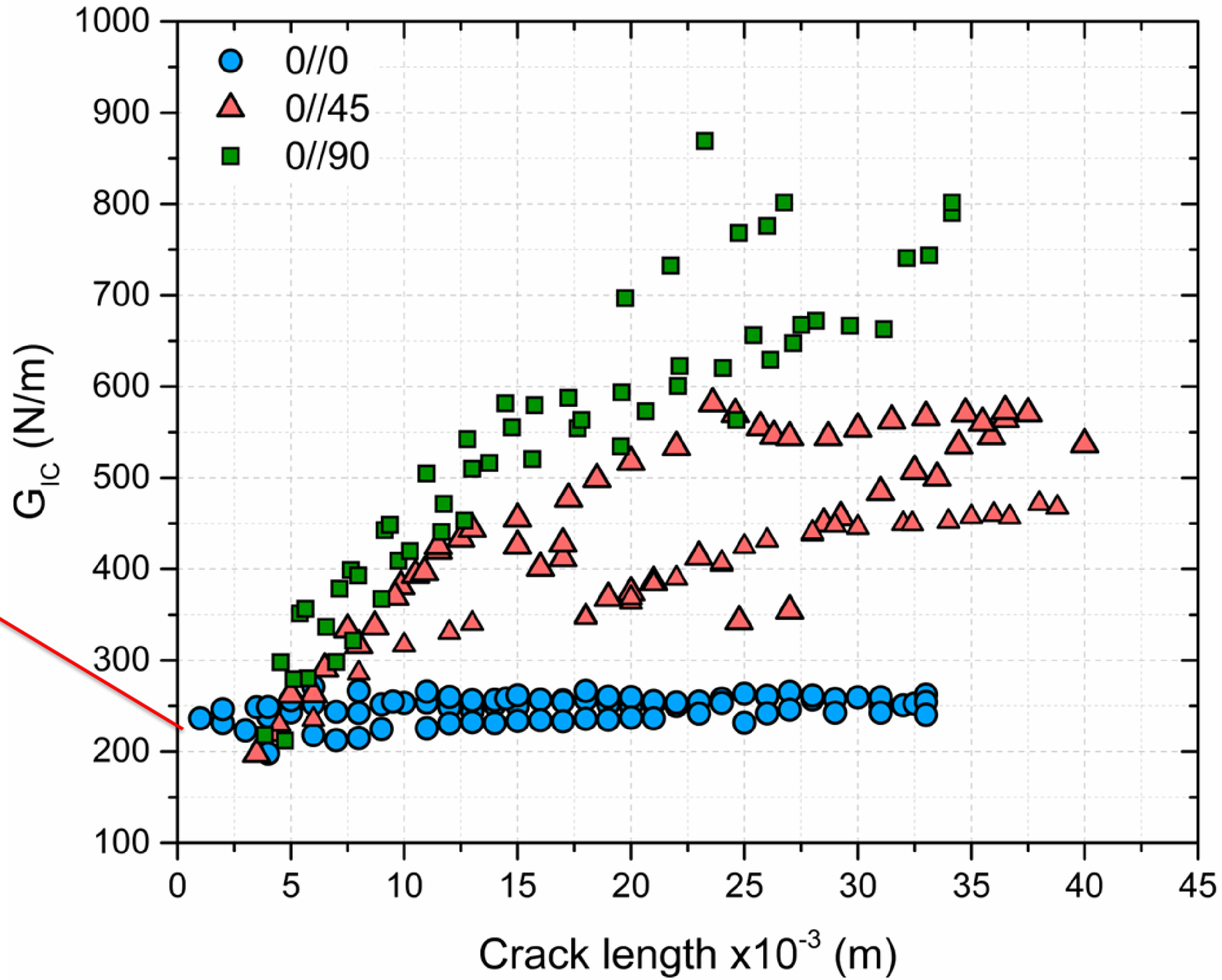


Quasi-static test



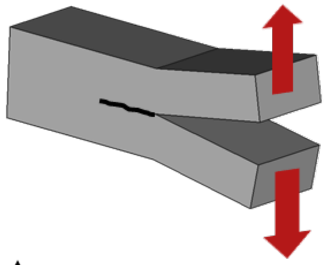
Quasi-static test

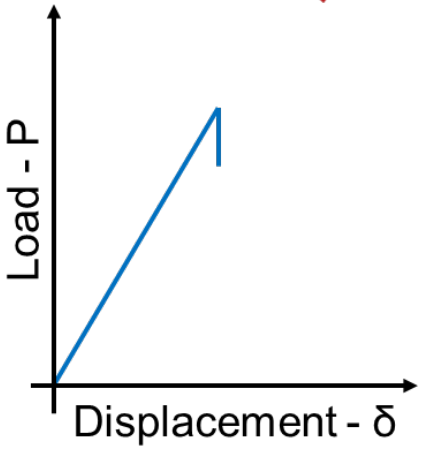




Fatigue test

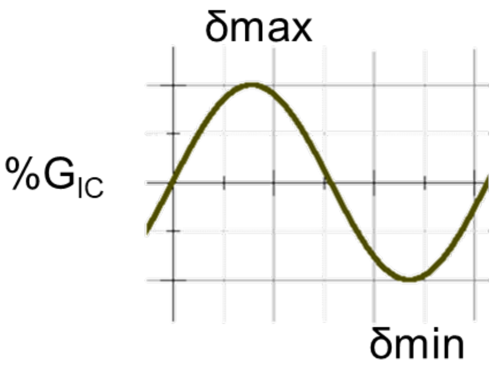
Pre-crack Quasi-static test



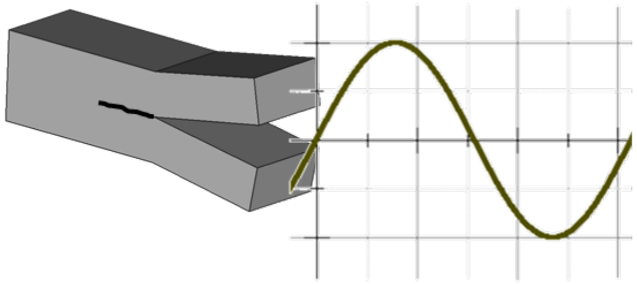


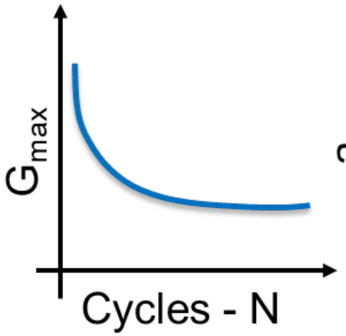
Determine Fatigue parameters

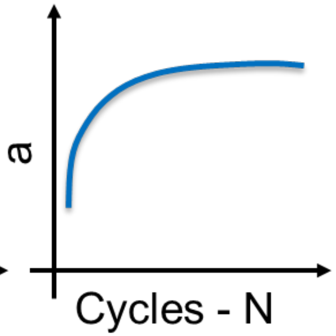
- ❑ Critical Load (P)
- ❑ Critical Displacement (δ)
- ❑ Crack length (*a*)
- ❑ Critical G (G_{IC})

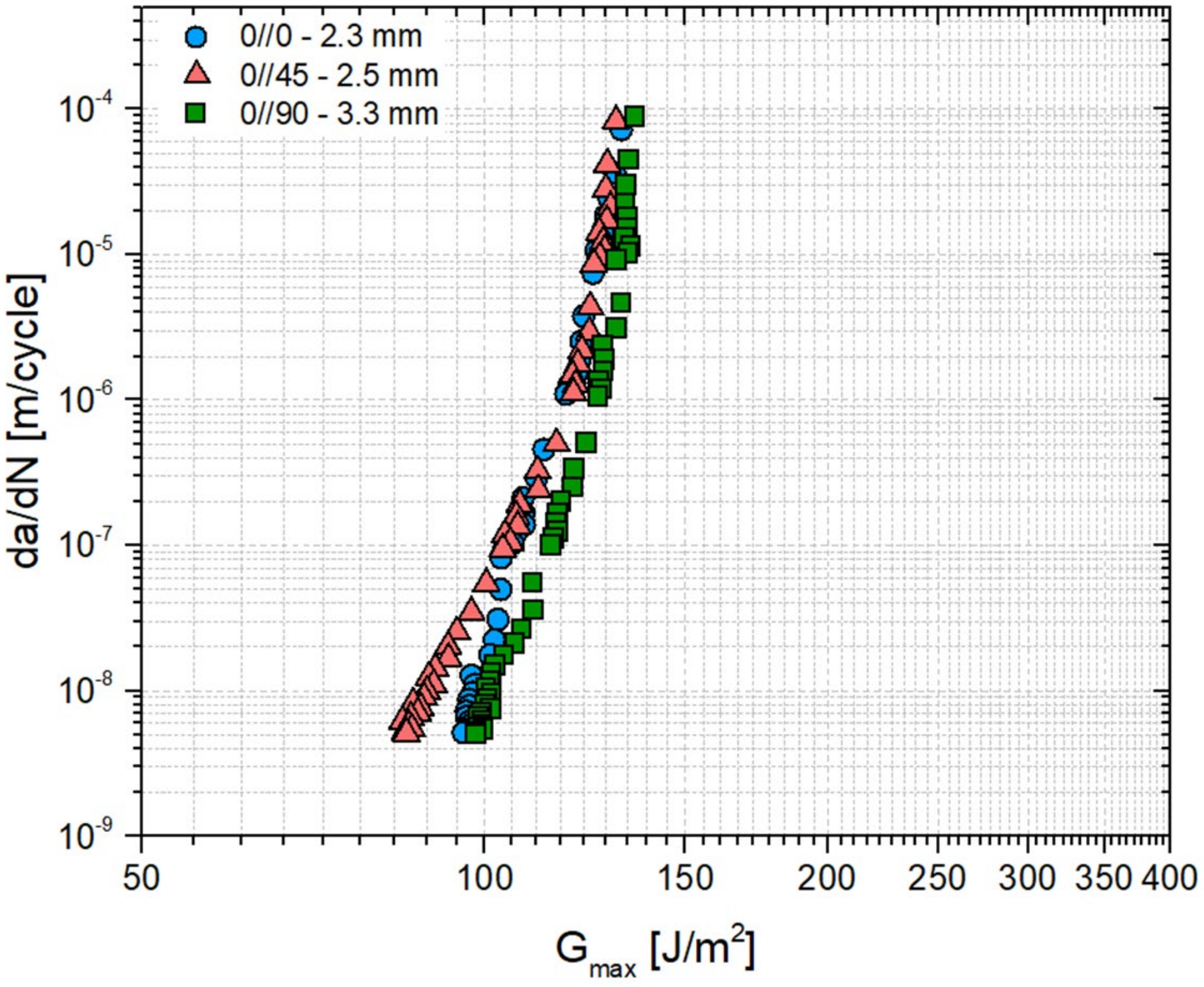


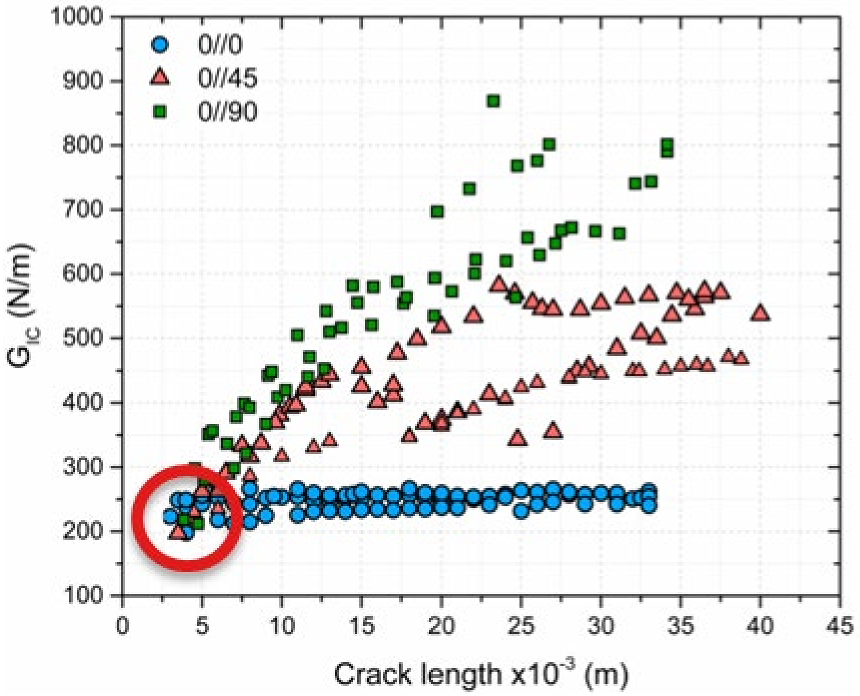
Fatigue test

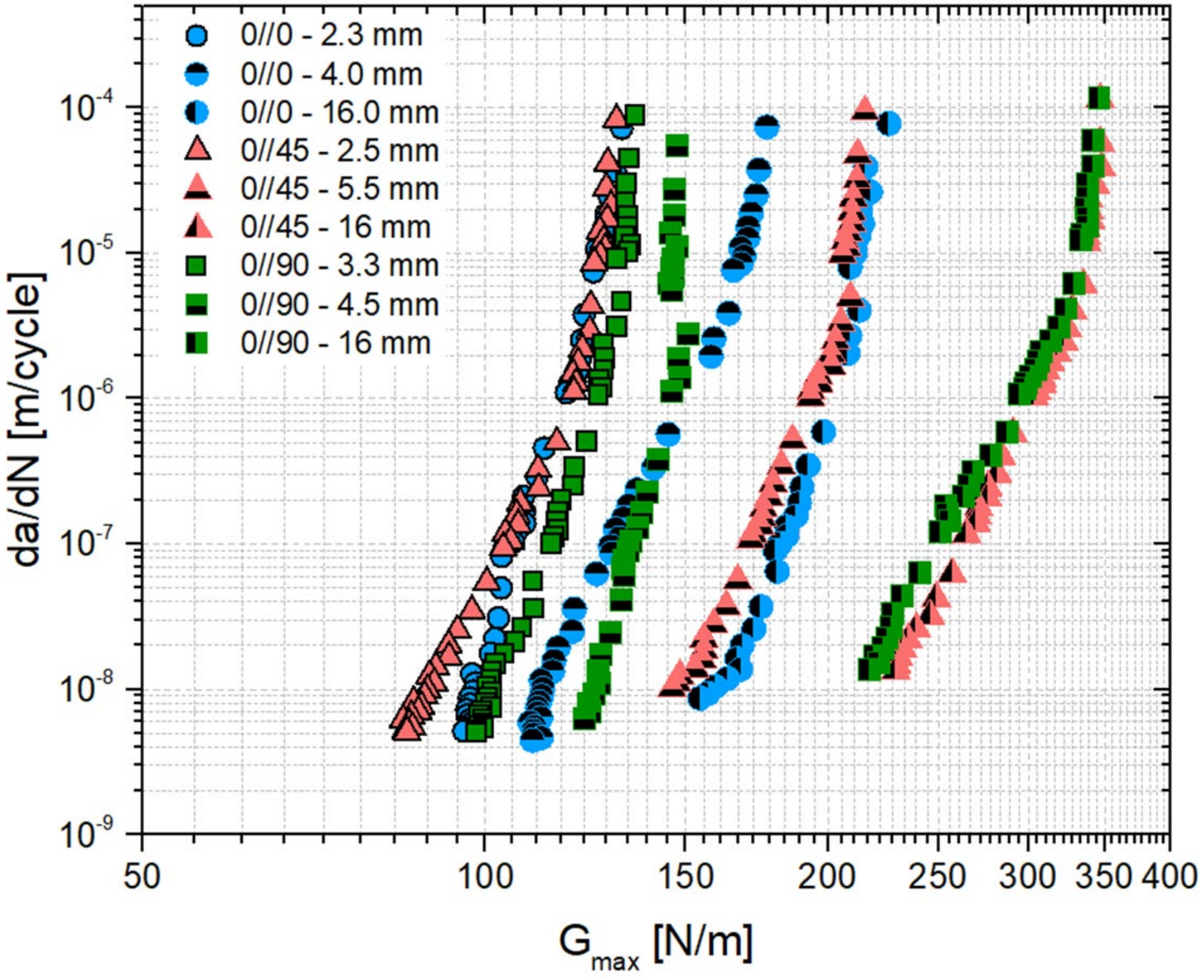


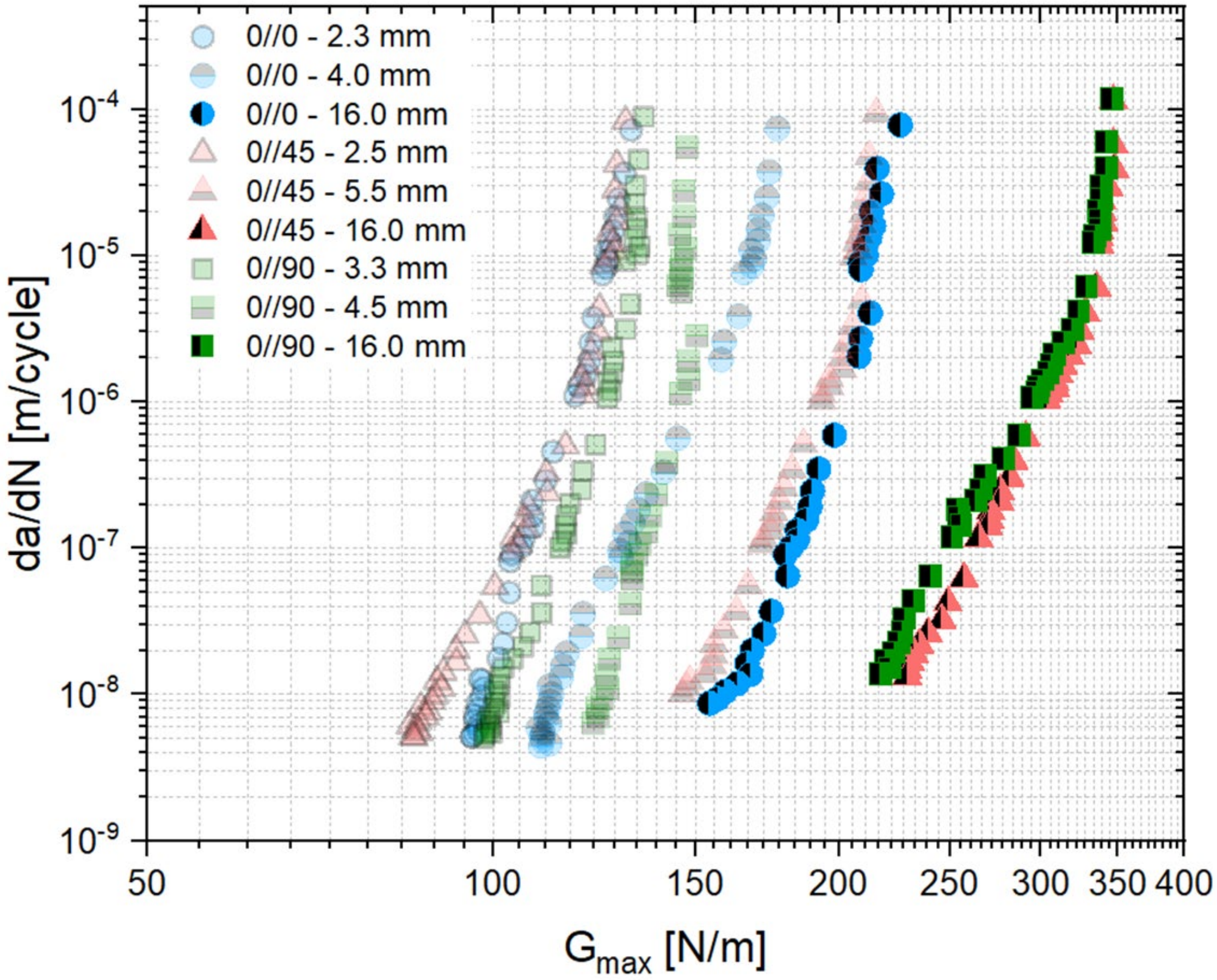





0//0 - 2.3 mm
0//45 - 2.5 mm
0//90 - 3.3 mm
da/dN [m/cycle]
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
50
100
150
200
250
300
350
400
G_{max} [J/m^2]


0//0
0//45
0//90
G_{IC} (N/m)
1000
900
800
700
600
500
400
300
200
100
0
5
10
15
20
25
30
35
40
45
Crack length x10^{-3} (m)

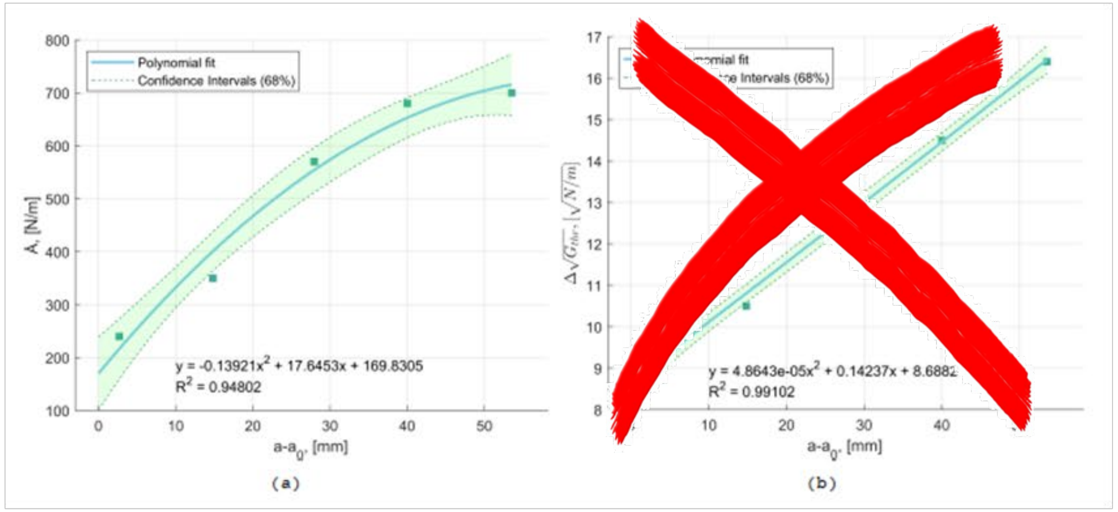

0//0 - 2.3 mm
0//0 - 4.0 mm
0//0 - 16.0 mm
0//45 - 2.5 mm
0//45 - 5.5 mm
0//45 - 16 mm
0//90 - 3.3 mm
0//90 - 4.5 mm
0//90 - 16 mm
da/dN [m/cycle]
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
50
100
150
200
250
300
350
400
G_{max} [N/m]


0//0 - 2.3 mm
0//0 - 4.0 mm
0//0 - 16.0 mm
0//45 - 2.5 mm
0//45 - 5.5 mm
0//45 - 16.0 mm
0//90 - 3.3 mm
0//90 - 4.5 mm
0//90 - 16.0 mm
da/dN [m/cycle]
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
50
100
150
200
250
300
350
400
G_{max} [N/m]

Removing the Fibre bridging effect

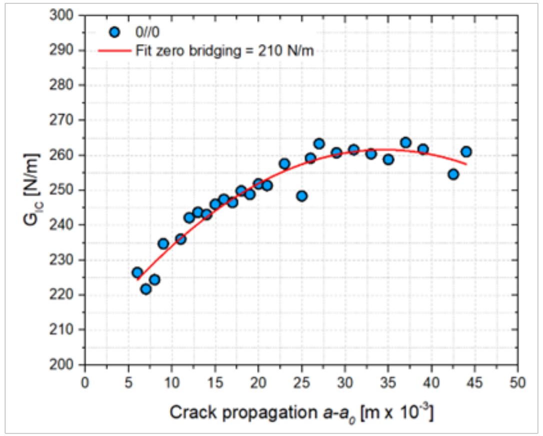
$$\frac{da}{dN} = C\left[\frac{\Delta\sqrt{G} - \Delta\sqrt{G_{thr}}}{\sqrt{1 - \sqrt{G_{max}}/\sqrt{G_{IC}}}}\right]^{\beta}$$

Determine Constants

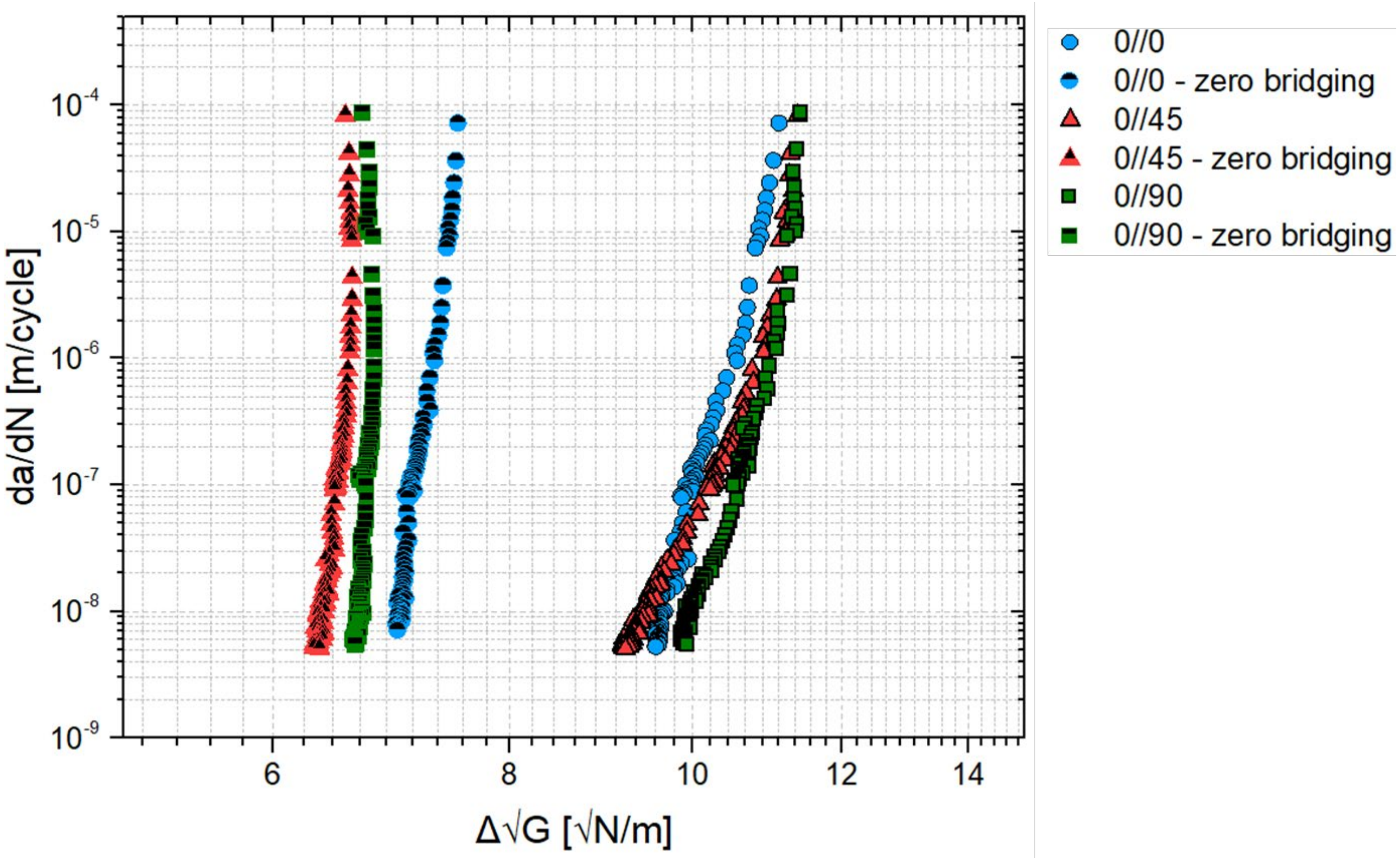


$$\frac{da}{dN} = C\left[\frac{\Delta\sqrt{G} - \Delta\sqrt{G_{thr}}}{\sqrt{1 - \sqrt{G_{max}}/\sqrt{G_{IC}}}}\right]^{\beta}$$

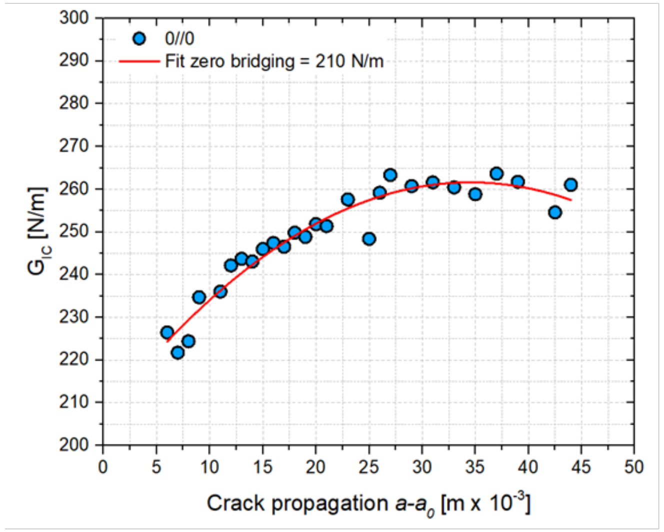
Determine Constants

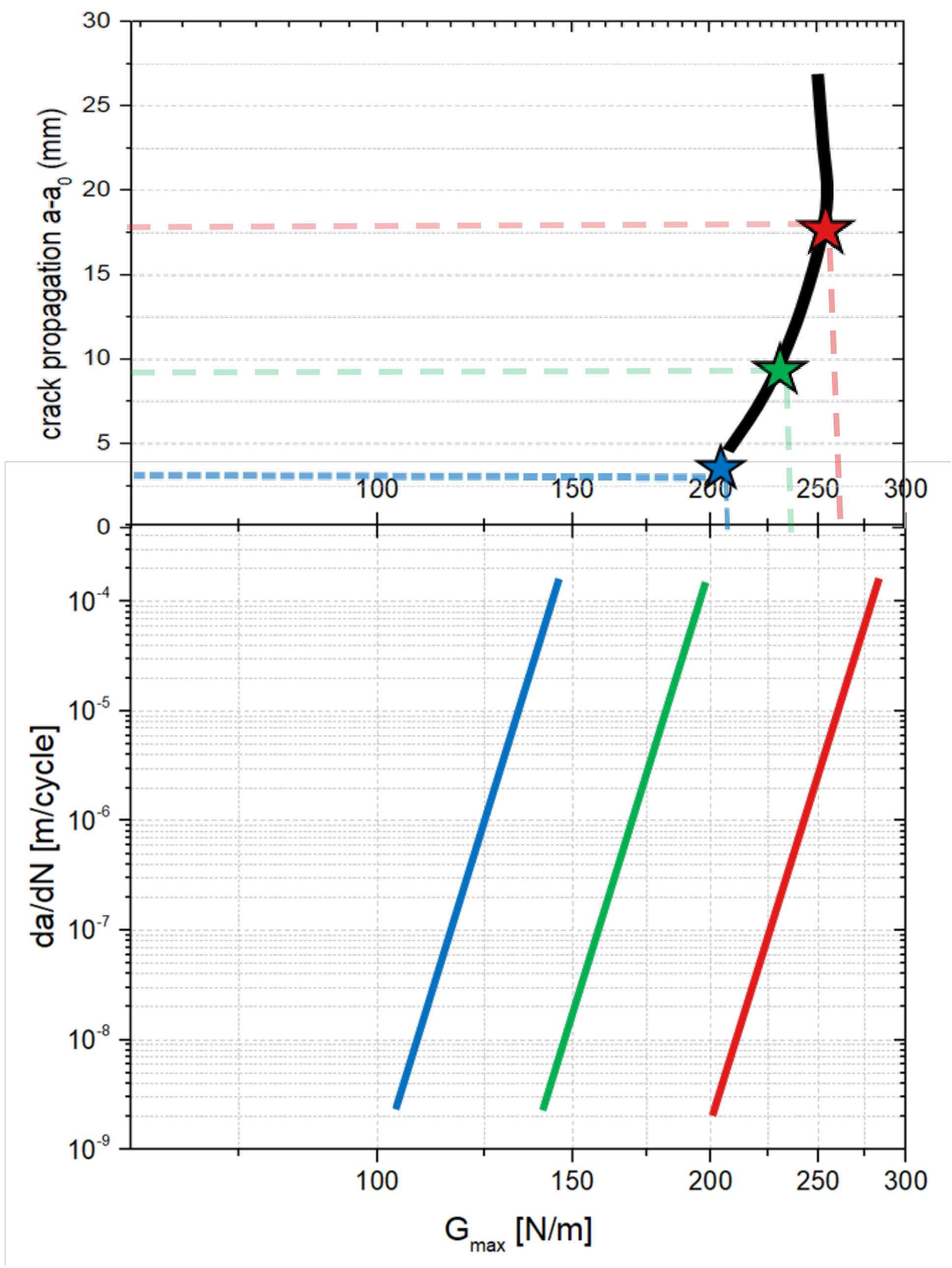


$$G_{thr,0} = G_{thr} \cdot \frac{G_{IC,0}}{G_{IC}}$$


da/dN [m/cycle]
10-4
10-5
10-6
10-7
10-8
10-9
6
8
10
12
14
Δ√G [√N/m]
0//0
0//0 - zero bridging
0//45
0//45 - zero bridging
0//90
0//90 - zero bridging

Adding the Fibre bridging effect

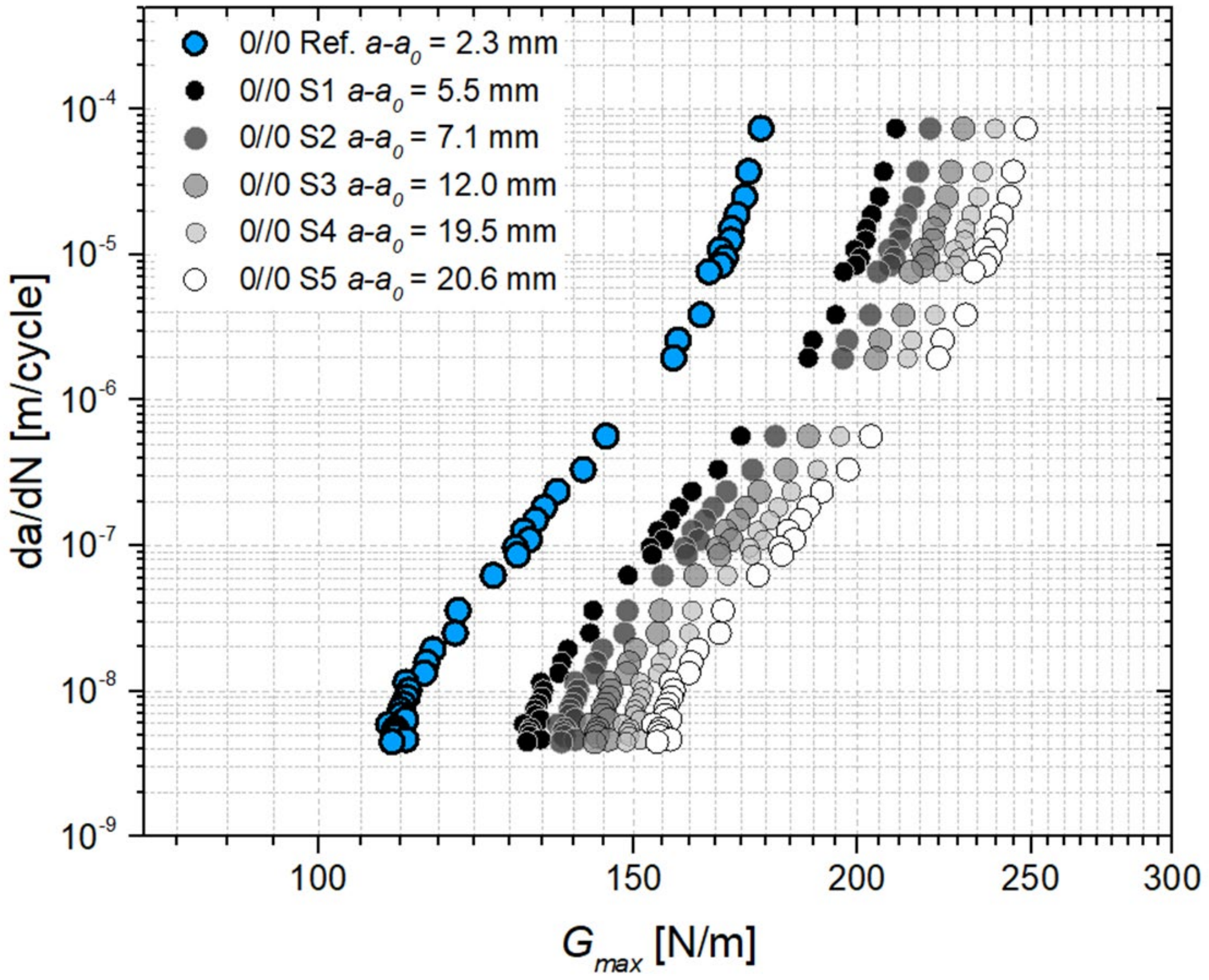




$$G_p = G_{max,i} \cdot \frac{G_{IC,static}}{G_{IC,ref}}$$

Adding the Fibre bridging effect

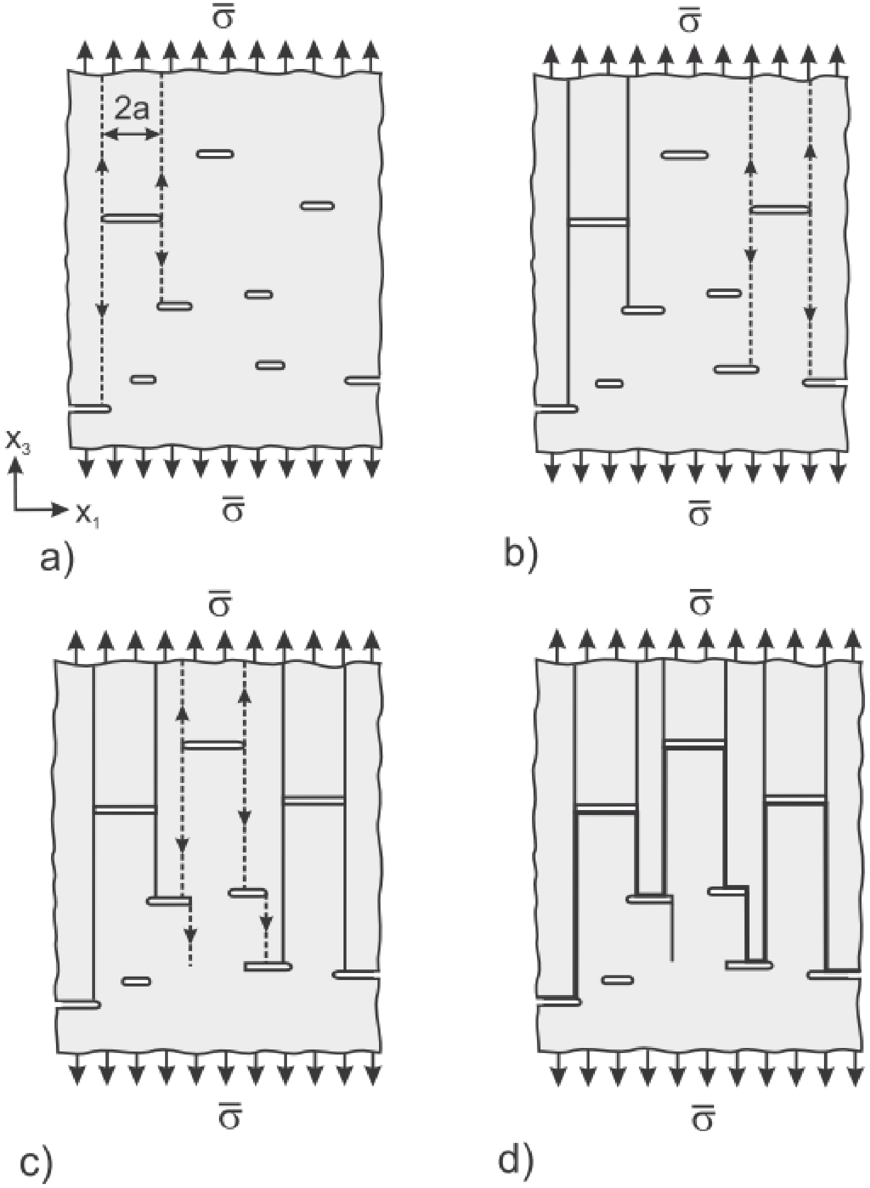
$$G_p = G_{max,i} \cdot \frac{G_{IC,static}}{G_{IC,ref}}$$



Summary

- Fatigue damage growth in composites is a complex process
  - Matrix cracks, fibre fracture, delamination
  - Distributed damage
  - Interaction between damage modes
- Delamination can be predicted by calculating SERR
- Fibre bridging affects growth rate at a given SERR
- Fibre orientation affects fibre bridging effect
- Fibre bridging must be taken into account to capture the effect of fibre orientation in the Paris fatigue curves

Back-up Slides



Sørensen *Composites Science and Technology 172 (2019) 172–181*

Final failure when fibre break clusters too large, or if clusters link up

Thank you!

Contact points for any question:

- Presenters
  - John-Alan PASCOE(TU Delft)
  - Email: j.a.pascoe@tudelft.nl

  - Francisco MONTICELI(TU Delft)
  - Email: f.m.monticeli@tudelft.nl

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for Durability Modelling of Composites

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