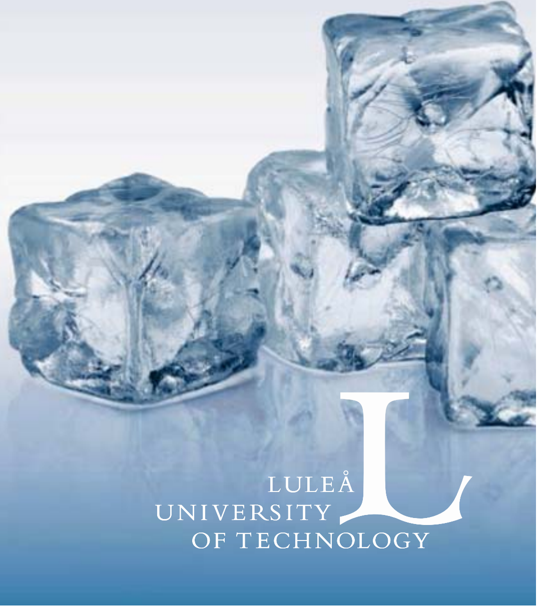
THE NORTHERNMOST UNIVERSITY
of Technology in Scandinavia

Determination of fiber/matrix interface debond growth parameters from cyclic loading of single fiber composites

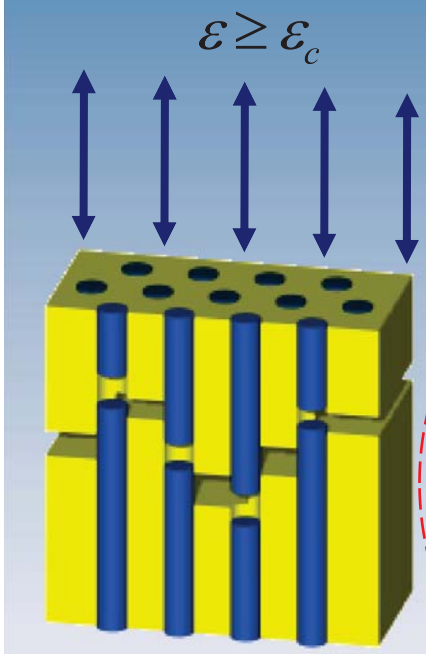
Andrejs Pupurs[1,2], Janis Varna[1], Povl Brøndsted[3], Stergios Goutianos[3]

[1]Luleå University of Technology, S-97187 Luleå, Sweden
[2]Swerea SICOMP, SE-94126 Piteå, Sweden
[3]Technical University of Denmark, Risø Campus, DK-4000 Roskilde, Denmark

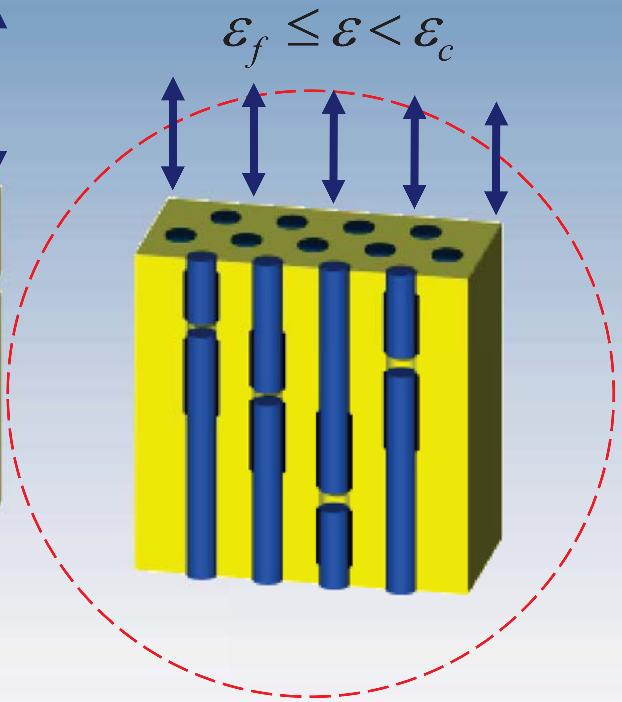


6th International Conference on Composites Testing and Model Identification (CompTest 2013) 22-24 April 2013, Aalborg, Denmark.

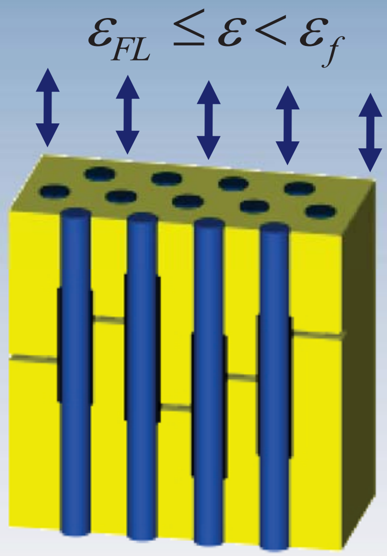
Fatigue damage in UD composites



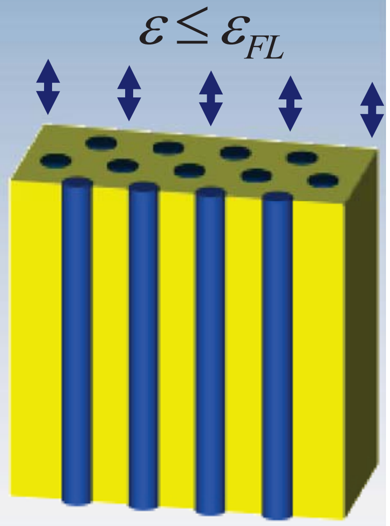
Failure of composite similar to static failure. Random fiber breaks and failure in few load cycles. N=1



Random fiber breaks during first cycle, N=1. Further damage development in form of growing fiber/matrix interface debond cracks.



After certain amount of load cycles, aligned matrix cracks appear and propagate as debond cracks. Bridged cracks followed by new fiber cracks

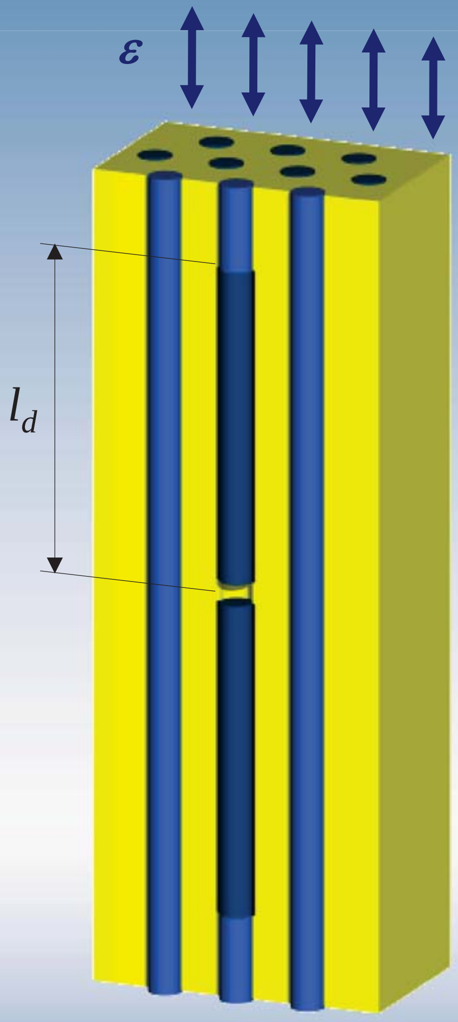


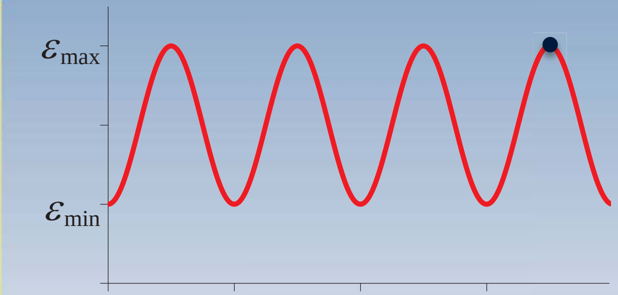
Applied strain level is too low (below fatigue limit). N=∞

Objective

- To focus on fiber/matrix interface debond growth in tension-tension fatigue
- To use fracture mechanics (energy release rate) for the debond growth analysis
- To calculate the energy release rate and to determine its dependence on debond length and to describe it by simple fitting function
- Using experimental data and the calculated energy release rate to evaluate whether a power law can describe the debond length growth rate in cyclic loading
- To determine material constants in this power law, if it is applicable

Debond growth in tension-tension fatigue





$$\varepsilon_{\max} > 0$$
$$\varepsilon_{\min} > 0$$

$$l_d = f(N)$$

Paris law: $$\frac{dA}{dN} = B(\Delta K)^m$$

dA – increase of the crack surface area

dN – increase of number of applied load cycles

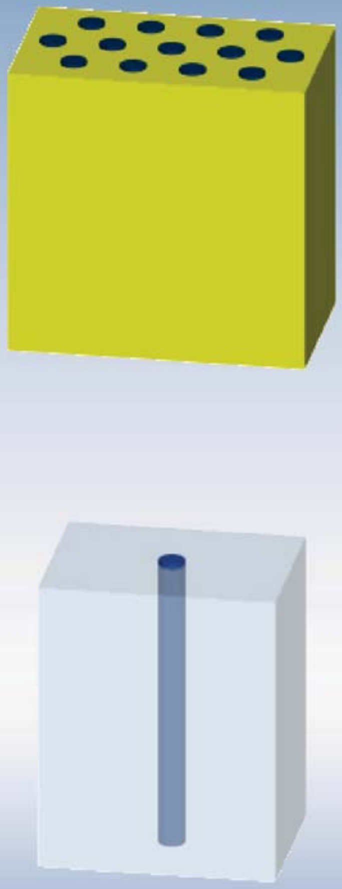
ΔK – stress intensity factor range

B, m – material constants

$$\frac{dA}{dN} = B(\Delta G_{II})^m \quad \Longrightarrow \quad \frac{dl_{dn}}{dN} = B^*(\Delta G_{II})^m$$

where $l_{dn} = l_d / r_f \quad B^* = B/2\pi r_f^2 \quad \Delta G_{II} = G(\varepsilon_{\max}) - G(\varepsilon_{\min})$

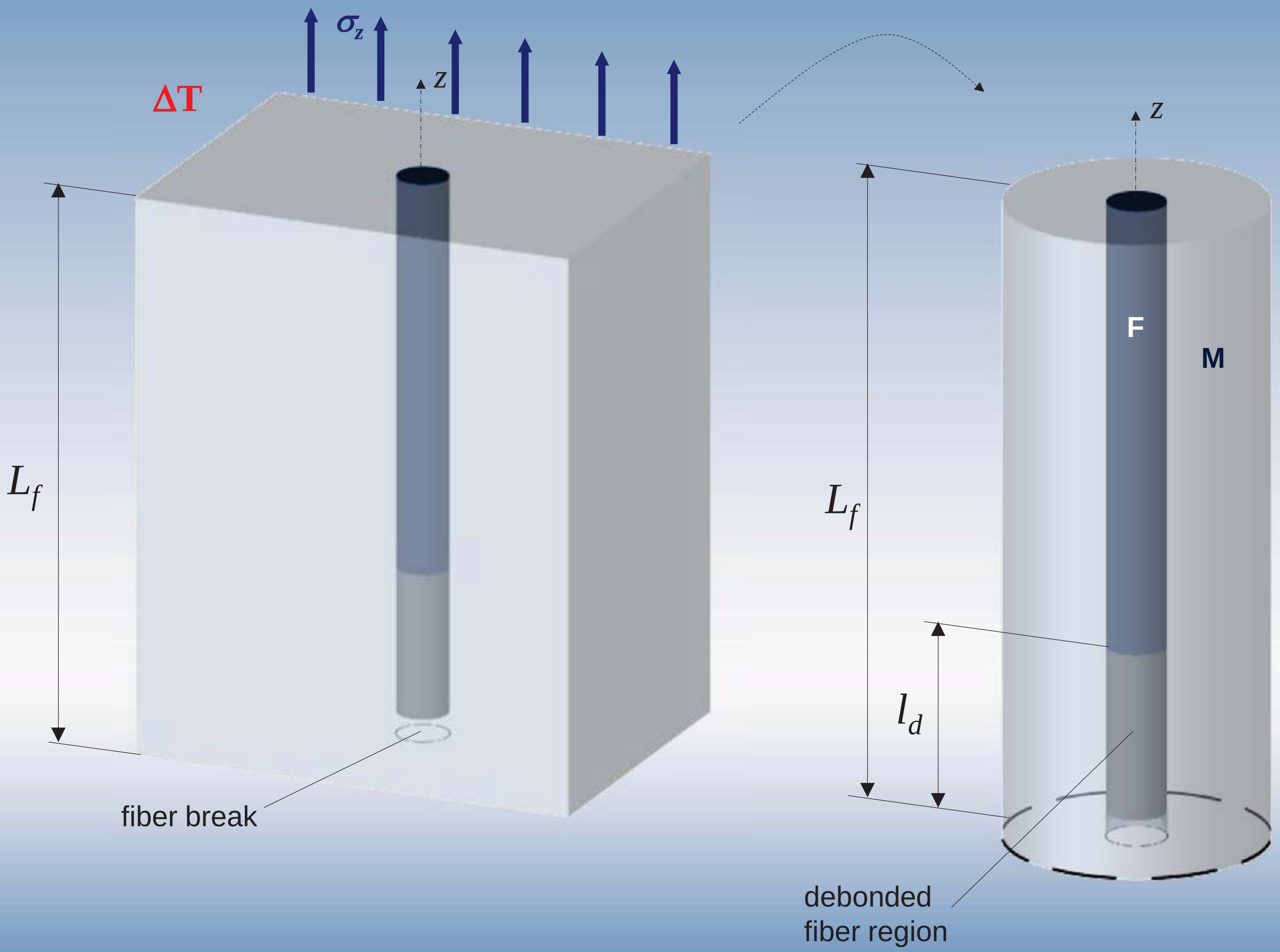
Determination of power law parameters



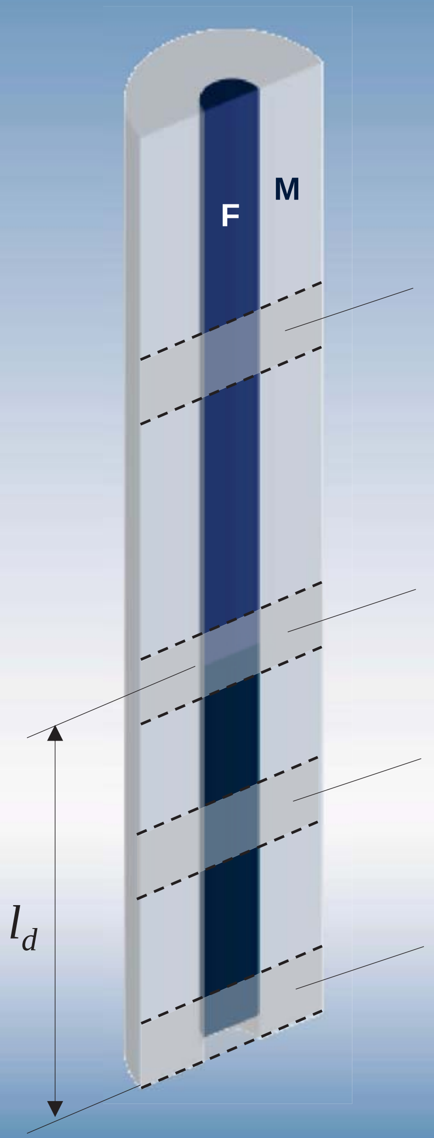
$$\frac{dl_{dn}}{dN} = B^{*}\left(\Delta G_{II}\right)^{m}$$

- Proper values of Paris law parameters m and B can only be found if experimental data of $l_d=f(N)$ are available.
- Experimental measurements of debond growth in fatigue is complicated for UD composites.
- **Single fiber (SF) composite** with transparent matrix, is a convenient tool to measure debond crack growth in cyclic loading.
- Analytical and FEM calculations of G_{II} for SF composites are necessary to account for the stress state.

Concentric cylinder model



Long and short debonds



Stress state regions

d) Plateau stress-state in bonded fiber region.

c) Debond tip region with stress singularity.

b) Plateau stress-state in debonded fiber region.

a) Very complex stress state at the fiber break.

- Long debonds
  - Debond growth in self-similar manner
  - Analytical model for G_{II} calculation
- Short debonds
  - Strong interaction between stress states in regions a) and c)
  - Numerical methods for G_{II} calculation

Analytical solution. Energy release rate for long debonds

$$G_{II} = \frac{E_z^f r_f}{4}\left(k_m^{\infty}\varepsilon_{mech} + k_{th}^{\infty}\left(\alpha_m - \alpha_z^f\right)\Delta T\right)^2$$

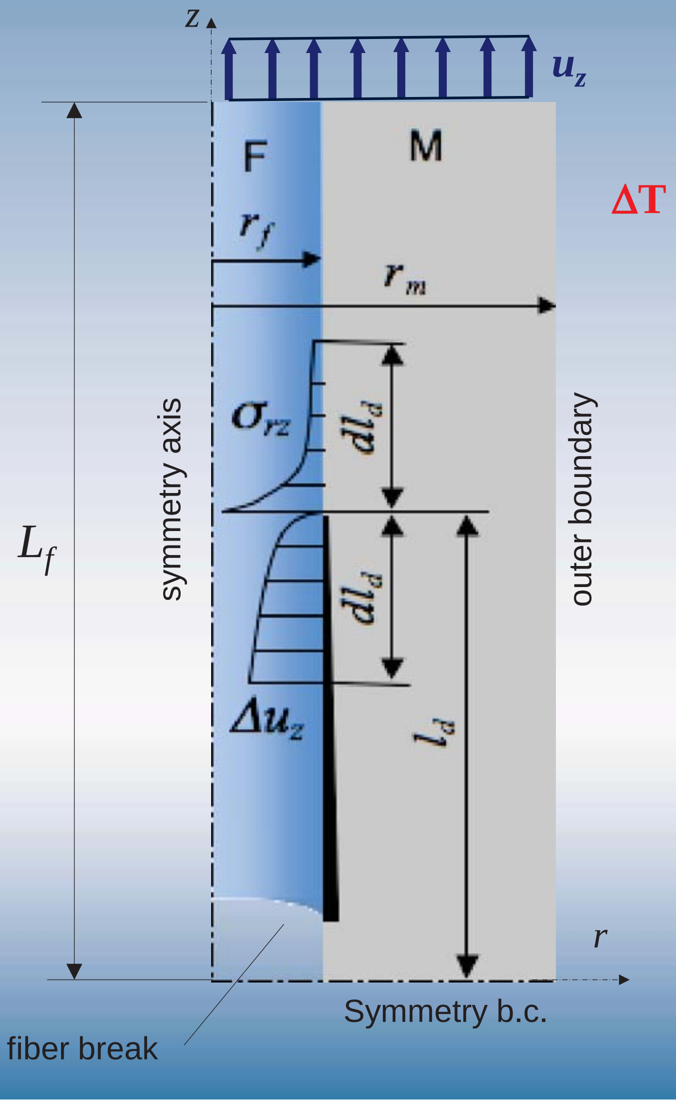
$$k_m^{\infty} = \left[\frac{2\nu_{zr}^f \nu_m}{E_z^f} - d_1\right]\frac{\sqrt{Q}}{d_2} \qquad k_{th}^{\infty} = \left[\frac{2\nu_{zr}^f}{E_z^f}\left(\alpha_r^f - \alpha_m\right) + d_1\left(\alpha_z^f - \alpha_m\right)\right]\frac{\sqrt{Q}}{d_2\left(\alpha_m - \alpha_z^f\right)}$$

$$d_1 = \frac{1-\nu_{r\theta}^f}{E_r^f} + \frac{1+\nu_m}{E_m} \qquad d_2 = \frac{2\left(\nu_{zr}^f\right)^2}{E_z^f} - d_1 \qquad Q = 1 - \frac{2\left(\nu_{zr}^f\right)^2}{E_z^f d_1}$$

- J.A. Nairn, Y.C. Liu, On the use of energy methods for interpretation of results of single-fiber fragmentation experiments, Composite Interfaces, vol.4, pp. 241-267, 1996.

		E_m = 3 [GPa]	E_m = 3.5 [GPa]	E_m = 4 [GPa]
ν_m = 0.3	k_m^{∞}	0.997427	0.997011	0.996598
	k_{th}^{∞}	1.014151	1.016443	1.018716

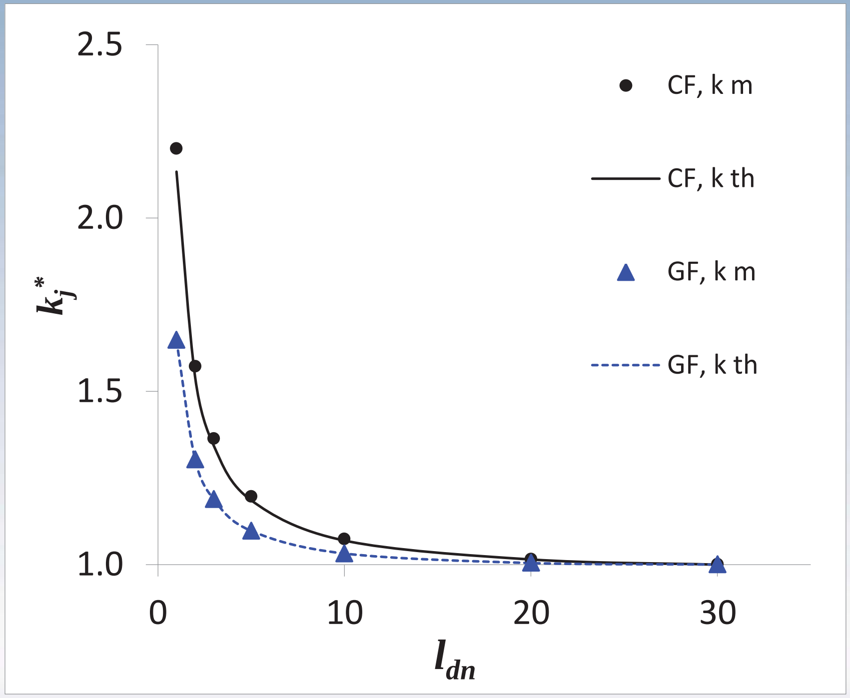
Numerical calculation of energy release rate for short debonds

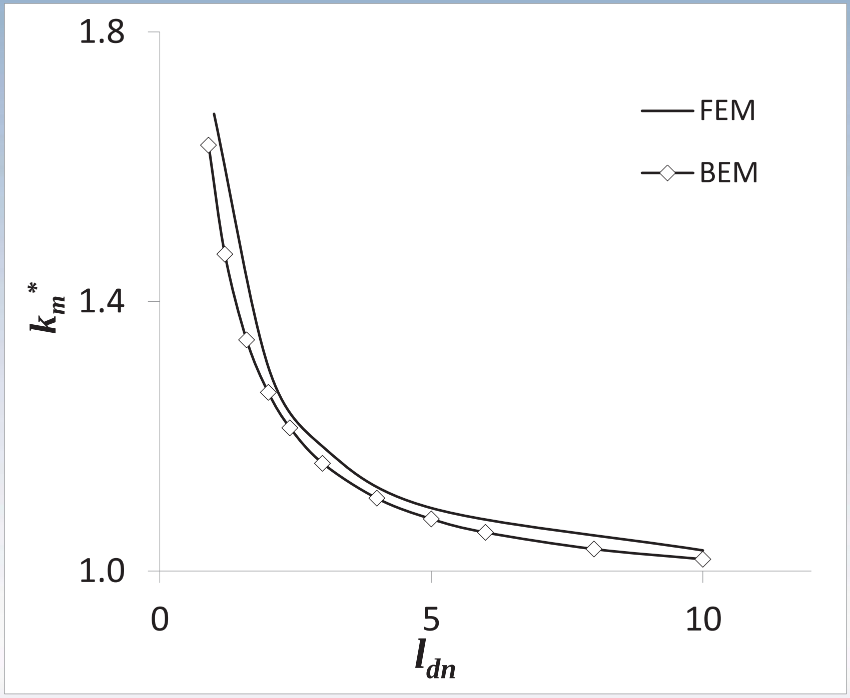


- Energy release rate calculation using Virtual Crack Closure Technique (VCCT)
- Calculations performed using FEM software ANSYS

$$G_{II}(l_d) = \lim_{dl_d \to 0} \frac{1}{2dl_d} \int_{l_d}^{l_d+dl_d} \Delta u^{l_d}(z - dl_d)\,\sigma_{rz}^{l_d}(z)\,dz$$

Magnification of energy release rate for short debonds





BEM results taken from:

- E. Graciani, V. Mantič, F. París, J. Varna, Numerical analysis of debond propagation in the Single Fibre Fragmentation Test, Composites Science and Technology, vol.69, pp. 2514-2520, 2009.

General expression for energy release rate

- Long debonds:

$$G_{II} = \frac{E_z^f r_f}{4}\left(k_m^\infty \varepsilon_{mech} + k_{th}^\infty\left(\alpha_m - \alpha_z^f\right)\Delta T\right)^2$$

- Short debonds:

$$k_m = k_m^*(l_{dn})k_m^\infty \qquad k_{th} = k_{th}^*(l_{dn})k_{th}^\infty$$

$$k_m^*(l_{dn}) = k_{th}^*(l_{dn}) = k_0(l_{dn})$$

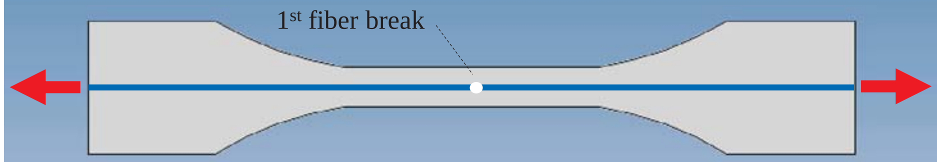
- Fitting the whole range:

$$k_0^2 = \begin{cases} 1 + \dfrac{a_1}{l_{dn}} + a_2 + a_3 l_{dn}; & 1 \le l_{dn} \le 30 \\ 1; & l_{dn} > 30 \end{cases}$$

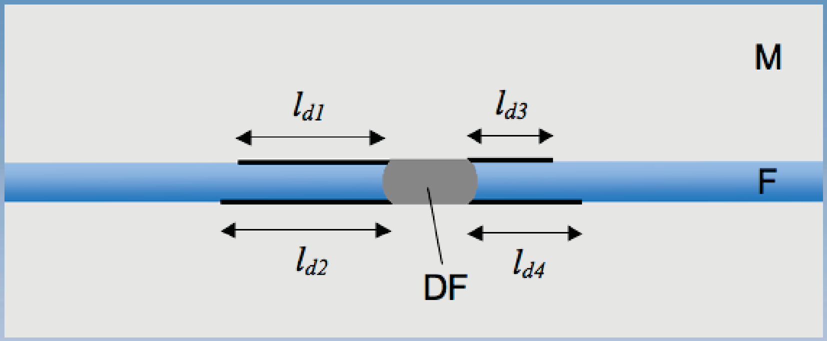
- Energy release rate change in one load cycle:

$$\boxed{\Delta G_{II}(l_{dn}) = \frac{r_f E_z^f k_0^2(l_{dn})}{4}\left[(\varepsilon_{mech}^{\max})^2 - (\varepsilon_{mech}^{\min})^2 + 2(\alpha_m - \alpha_z^f)\Delta T(\varepsilon_{mech}^{\max} - \varepsilon_{mech}^{\min})\right]}$$

Experimental measurements



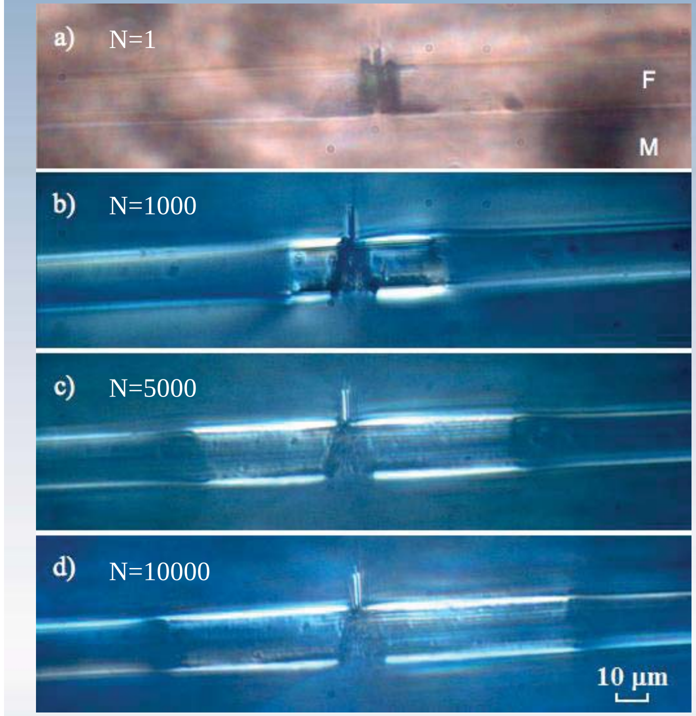
Glass fiber/Epoxy

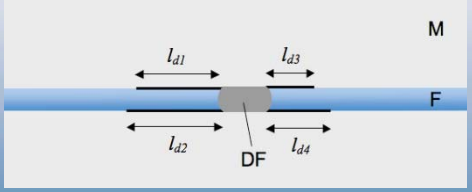


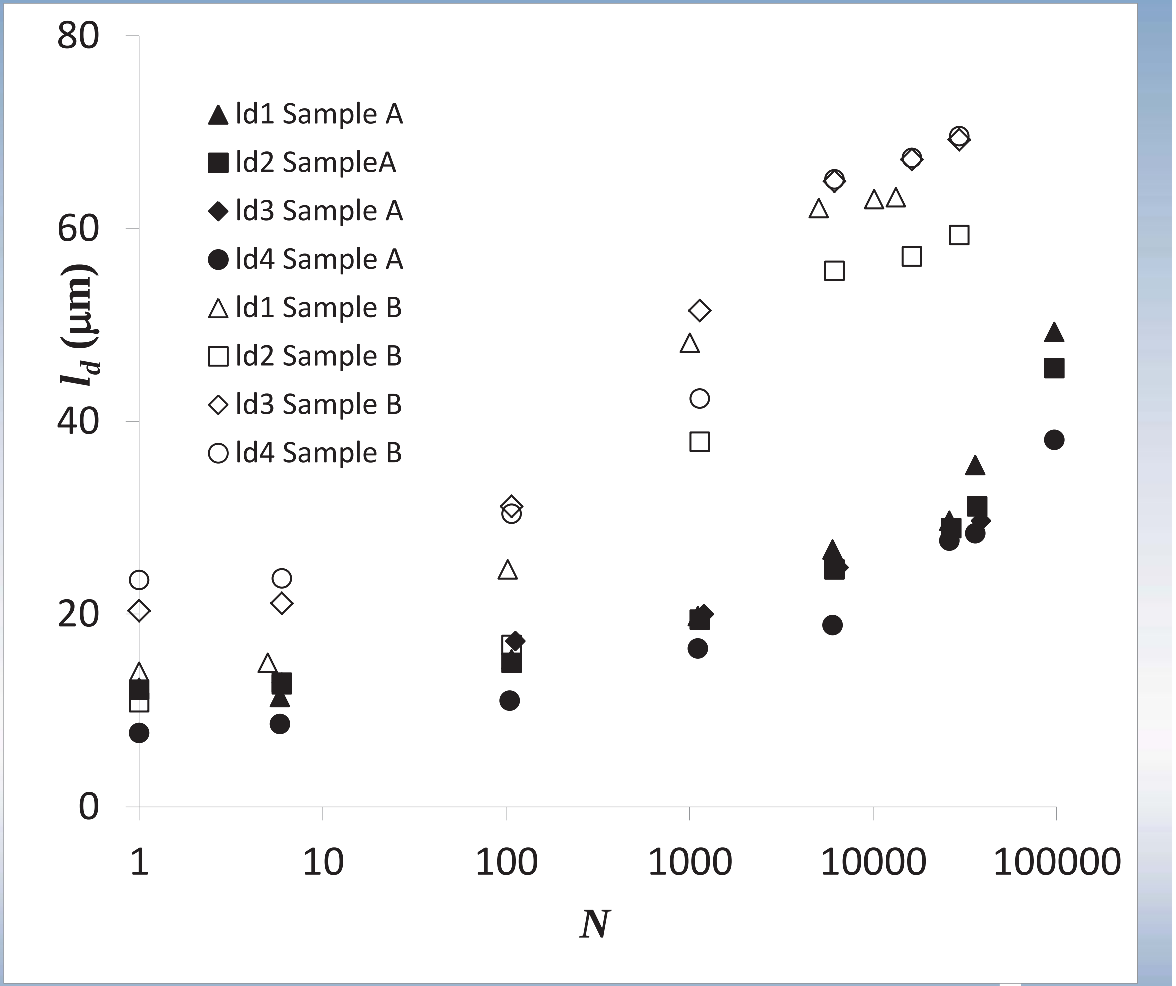
E_z^f [GPa]	ν_{zr}^f [-]	α_z^f [1/°C]	E_m [GPa]	ν_m [-]	α_m [1/°C]
70	0.20	$4.70 \cdot 10^{-6}$	3.17	0.33	$91.00 \cdot 10^{-6}$

- Fiber was pre-stressed with 7g of weight suspended at each end of fiber
- First a static load was applied until first break was initiated in fiber (σ_{1st})
- Tension-tension cyclic loading with frequency $f=2Hz$, $R=0.1$ was applied under load control. Measurements of debond length l_d were performed after selected number of load cycles.
- Two different values of maximal fatigue strain level were studied: Samples A, B: **ε_{max} = 1.76%**; Sample C: **ε_{max} = 1.32%**. The strain levels approximately correspond to 80% and 60% of the stress σ_{1st} respectively.

Experimental results. Debond growth in cyclic loading







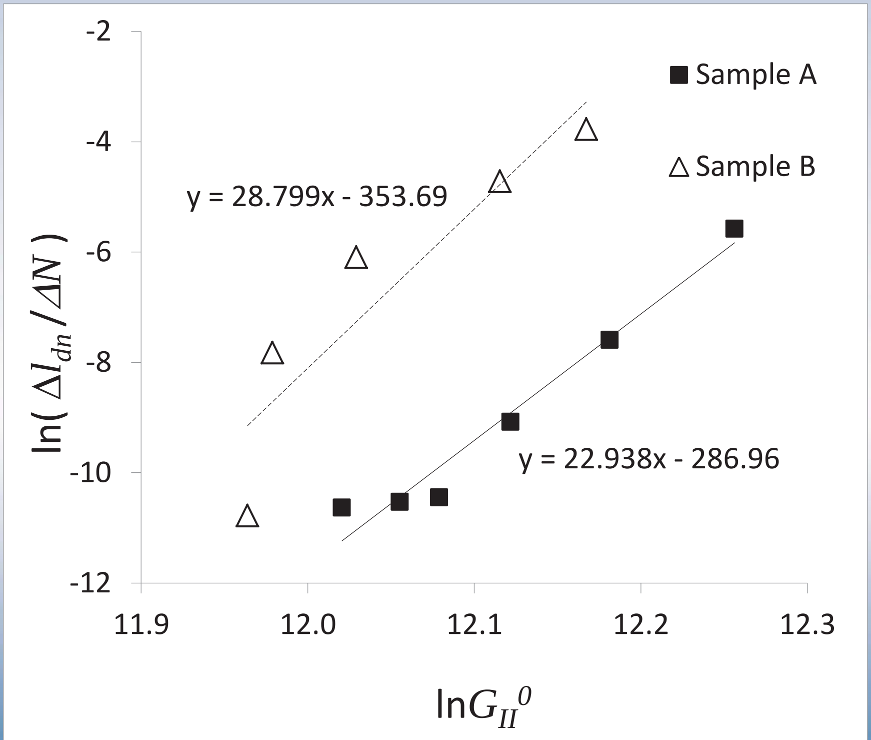
Determination of the power law parameters

$$\frac{dl_{dn}}{dN} = B^*\left(\Delta G_{II}\right)^m$$

$$\Delta G_{II}(l_{dn}) = \frac{r_f E_z^f k_0^2(l_{dn})}{4}\left[(\varepsilon_{mech}^{\max})^2 - (\varepsilon_{mech}^{\min})^2 + 2(\alpha_m - \alpha_z^f)\Delta T(\varepsilon_{mech}^{\max} - \varepsilon_{mech}^{\min})\right]$$

$$G_{II}^0 = \frac{r_f E_z^f k_0^2(l_{dn})}{4}$$

$$\Delta g = \left[(\varepsilon_{mech}^{\max})^2 - (\varepsilon_{mech}^{\min})^2 + 2(\alpha_m - \alpha_z^f)\Delta T(\varepsilon_{mech}^{\max} - \varepsilon_{mech}^{\min})\right]$$

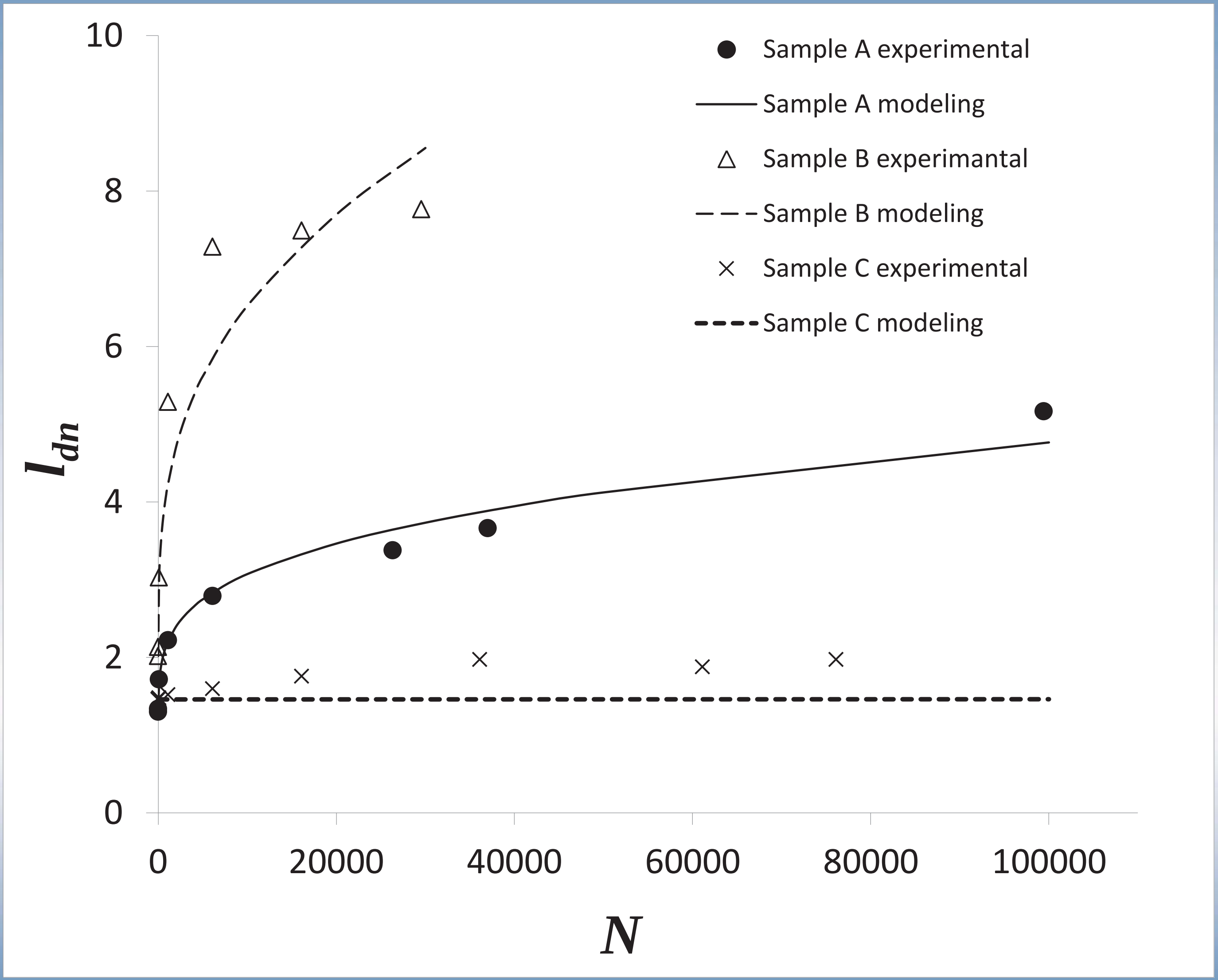


$$\frac{dl_{dn}}{dN} = B^*\left(G_{II}^0 \cdot \Delta g\right)^m$$

$$\ln\left(\frac{dl_{dn}}{dN}\right) = \ln B^* + m\ln G_{II}^0 + m\ln \Delta g$$

Sample	m	$\ln B^*$
A	22.94	-99.72
B	28.80	-118.60

Validation of power law parameters



Conclusions

- The strain energy release rate in Mode II for debond growth was analyzed combining analytical solution for long debonds and FEM solution for short debonds.
- Using the quantified debond length versus number of cycles data it was shown that the power law with respect to the strain energy release rate change is applicable for debond growth characterization in tension-tension fatigue.
- Simulations showed that the obtained parameters give acceptable predictions for cases, when the debond grows as well as when it does not grow.
- Being material properties the power law parameters determined in this study using single fiber composites can also be applied for the case of UD composites made of the same material system

Related papers

- A. Pupurs, S. Goutianos, P. Brøndsted, J. Varna, Interface debond crack growth in tension-tension cyclic loading of single fiber polymer composites, Composites Part A, vol.44, pp. 86-94, 2013.
- A. Pupurs, J. Varna, FEM modeling of fiber/matrix debond growth in tension-tension cyclic loading of unidirectional composites, International Journal of Damage Mechanics, In Press, 2013. (available online)

Thank you for your attention!