Fatigue of Composite Materials

Lectures in
IIMEC 2012 Summer School on
Advanced Composite Materials
Technical Educational Institute, Serres, Greece

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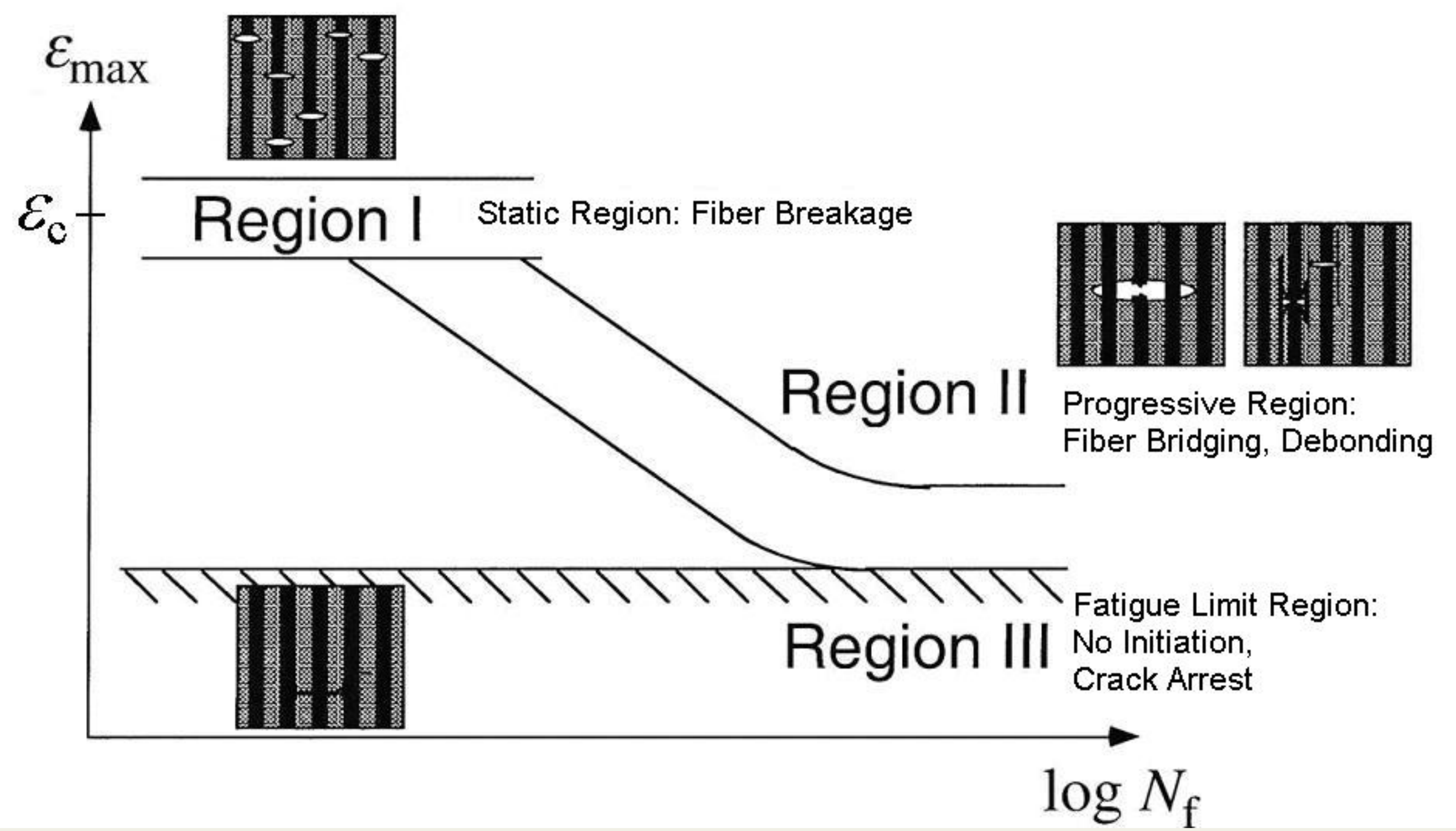
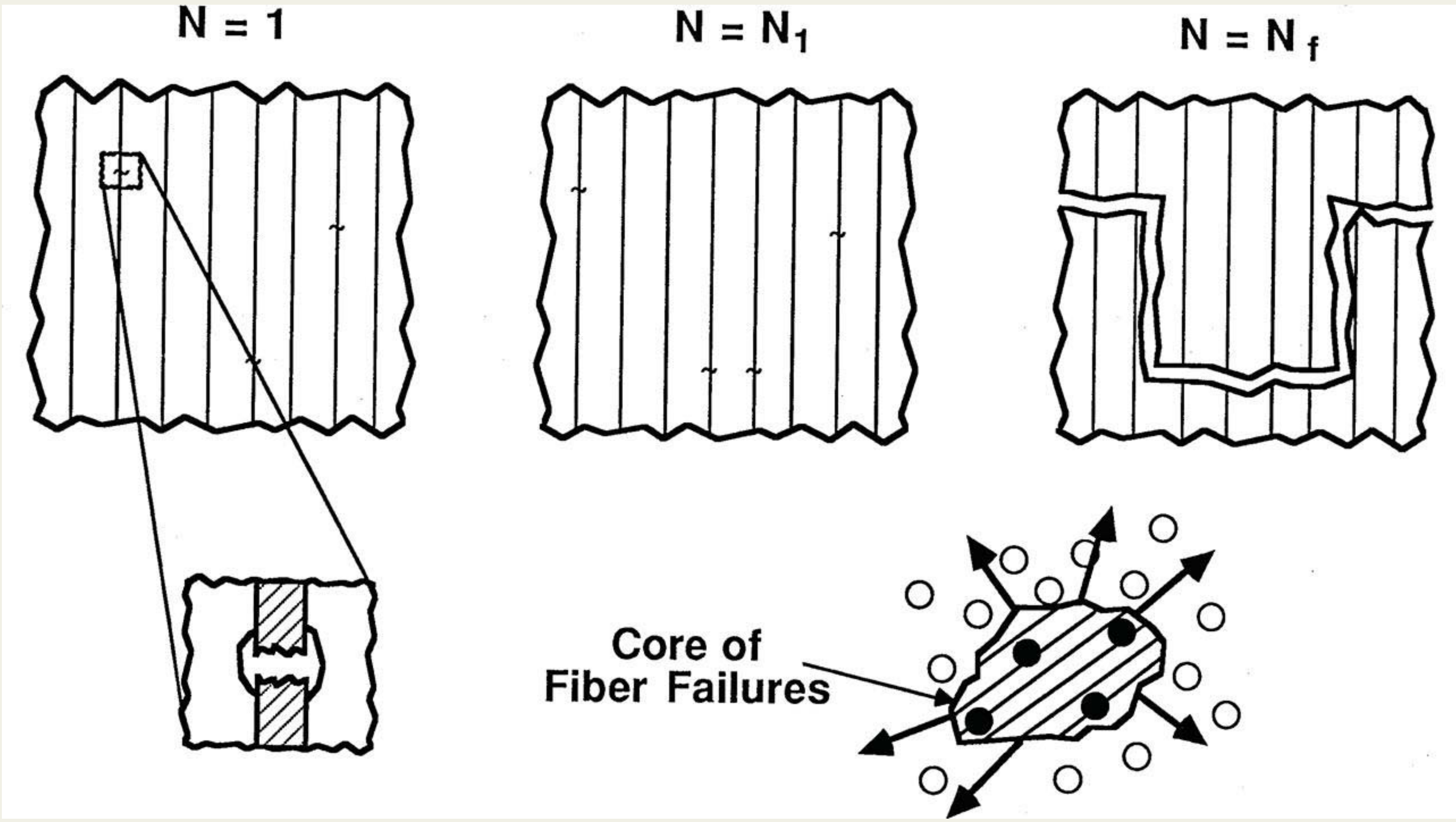
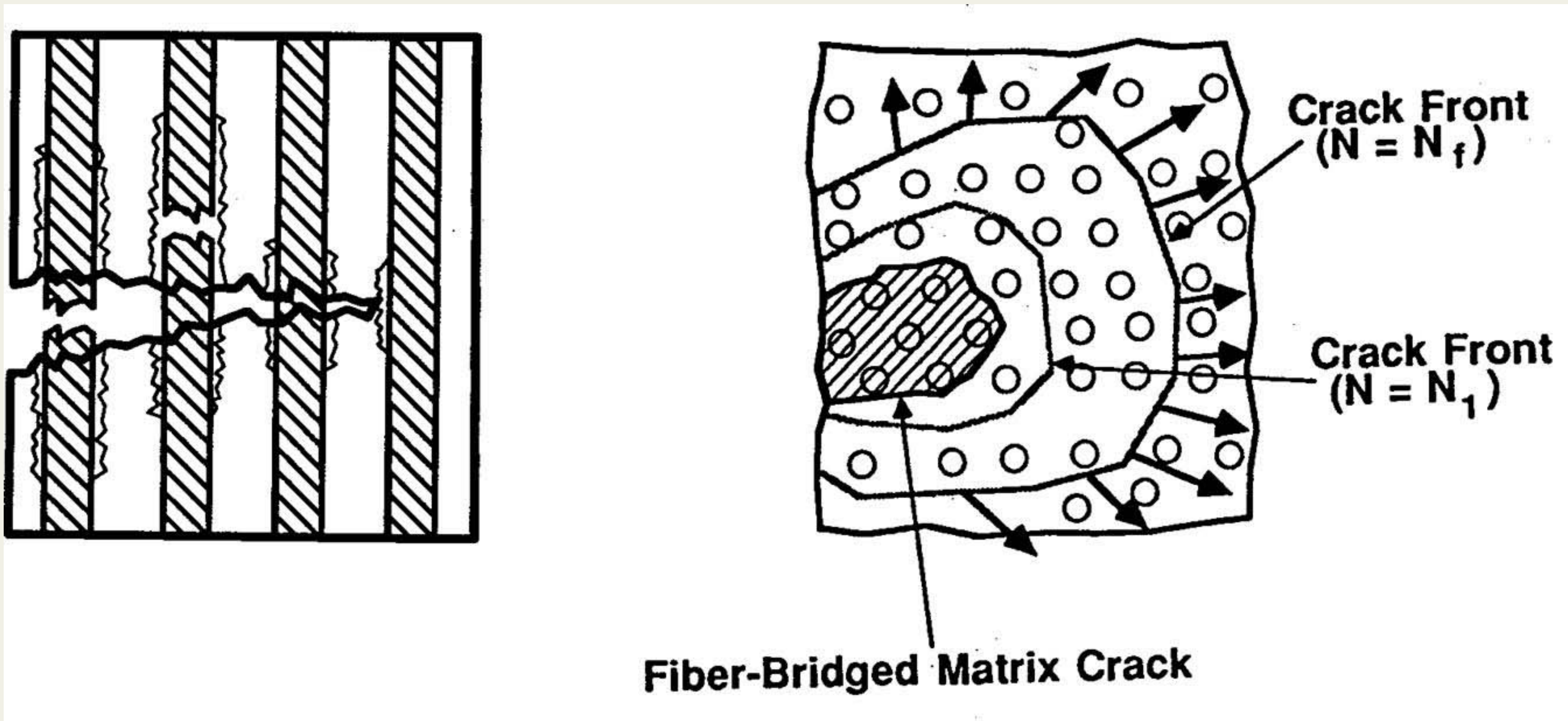
The Fatigue Life Diagram
Unidirectional Composites
On-axis tension-tension fatigue



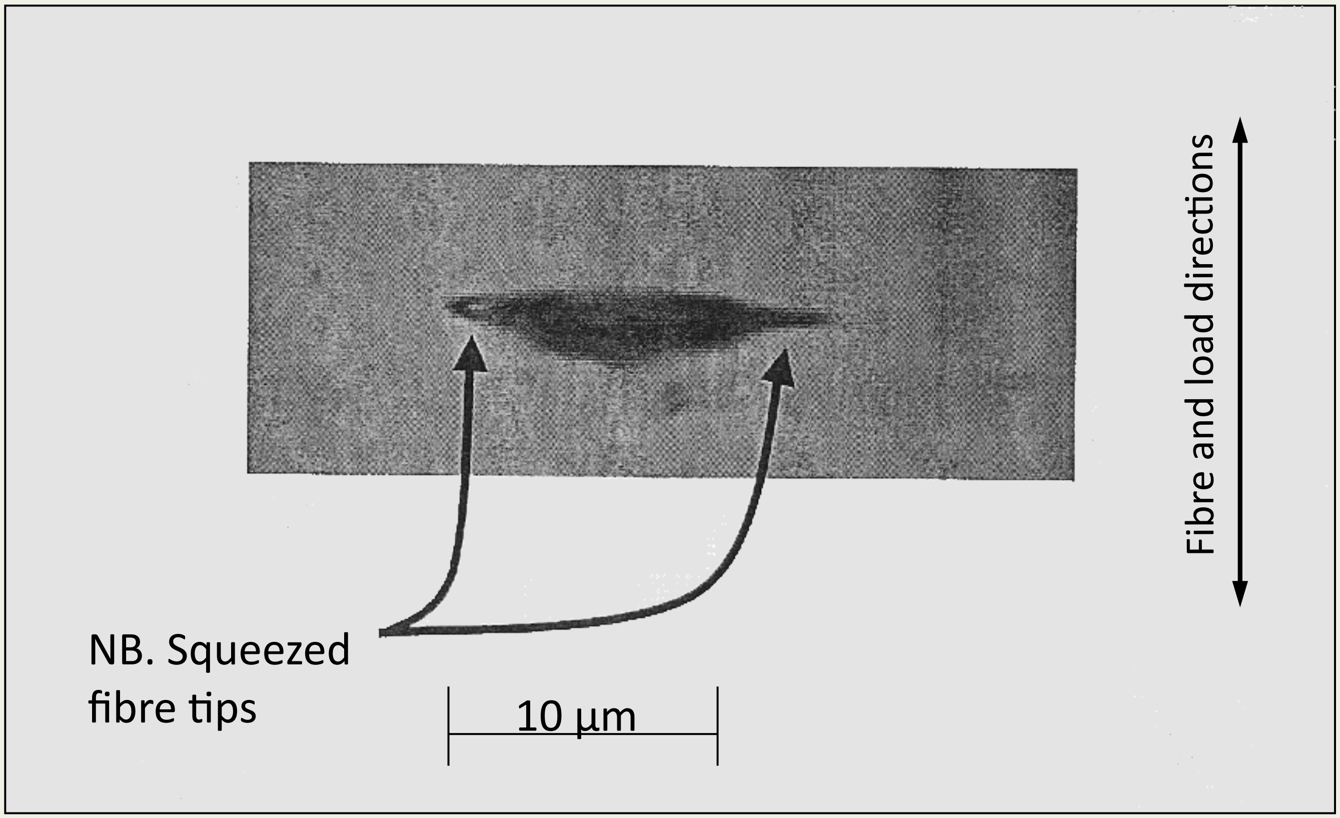
Mechanisms – Region I (Non-progressive)



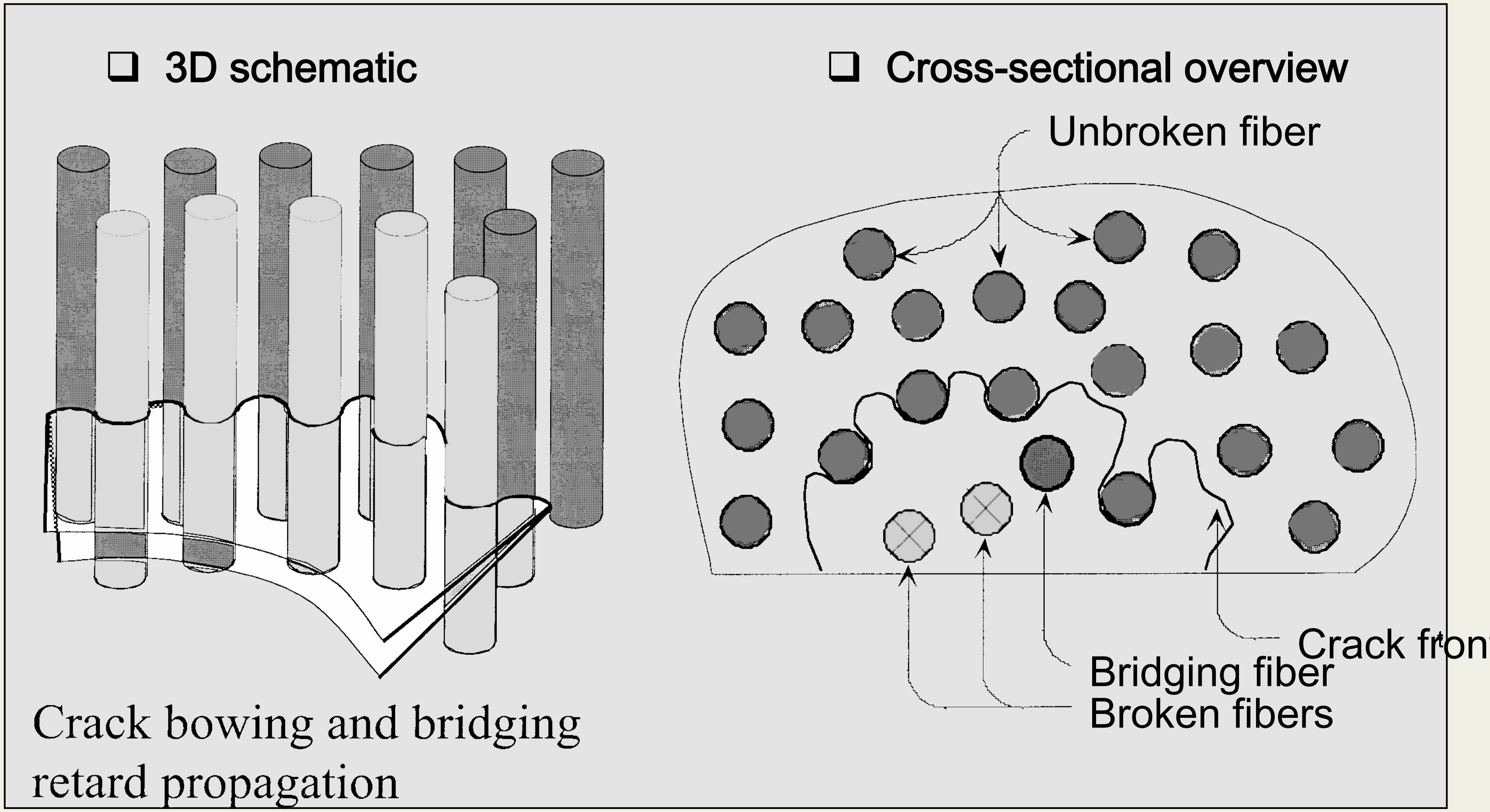
Mechanisms – Region II
Fiber-bridged Matrix Cracking



CF/epoxy
Damage mechanisms in Region II



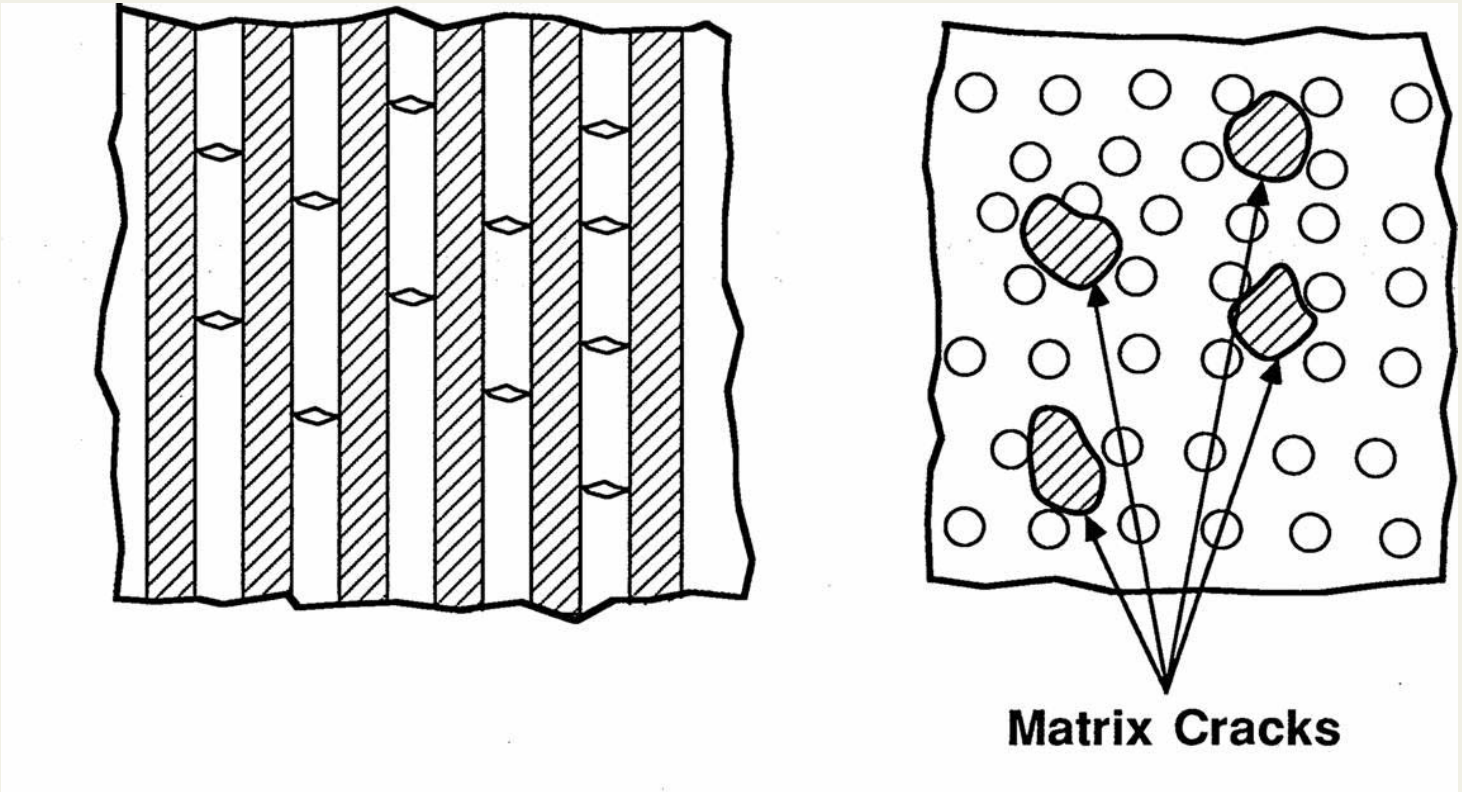
Fibre-bridged cracking



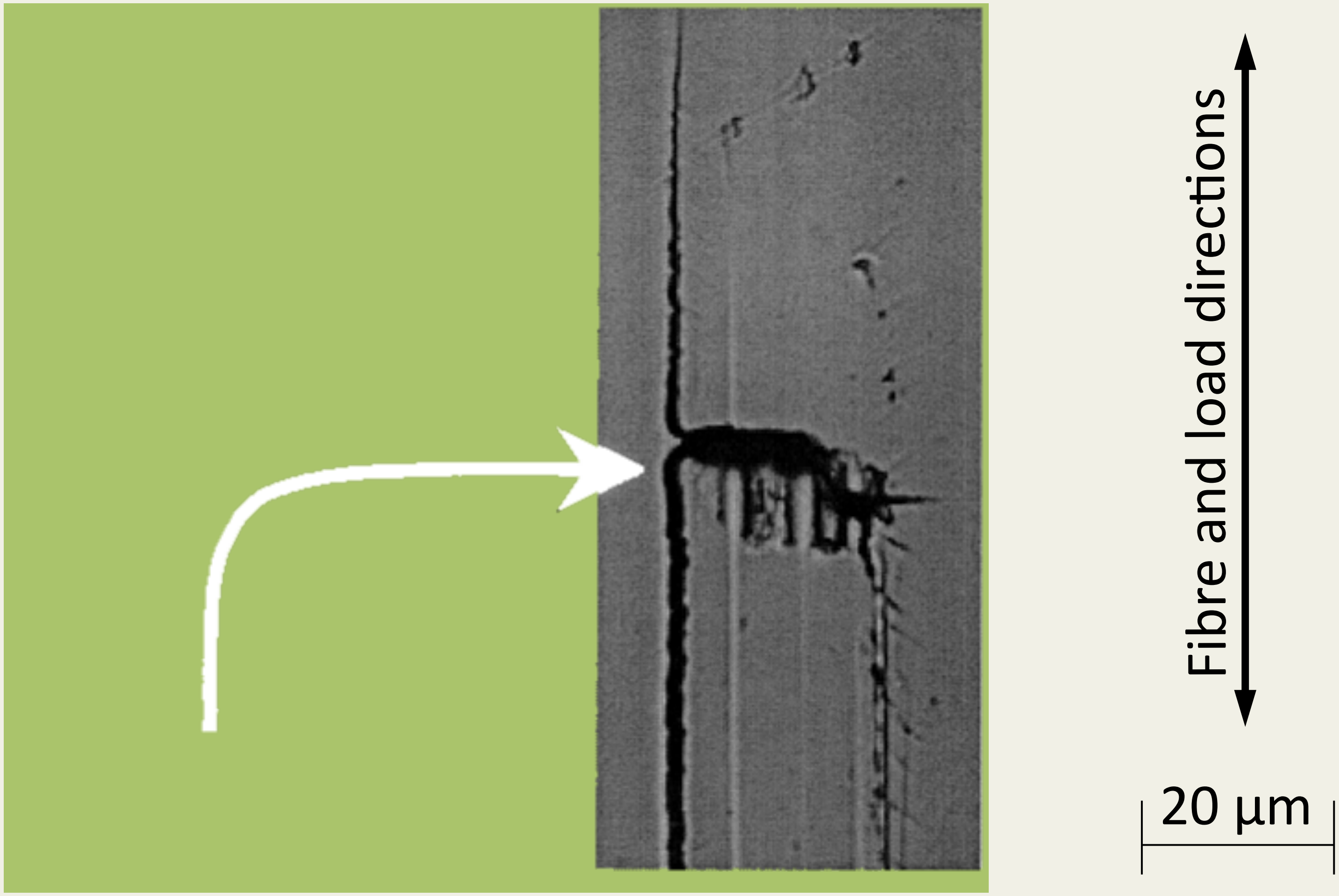
Mechanism – Region III

Non-evolving matrix cracking

Mechanism: Matrix Cracking Between Fibers



Cracking arrested at the interface by debonding

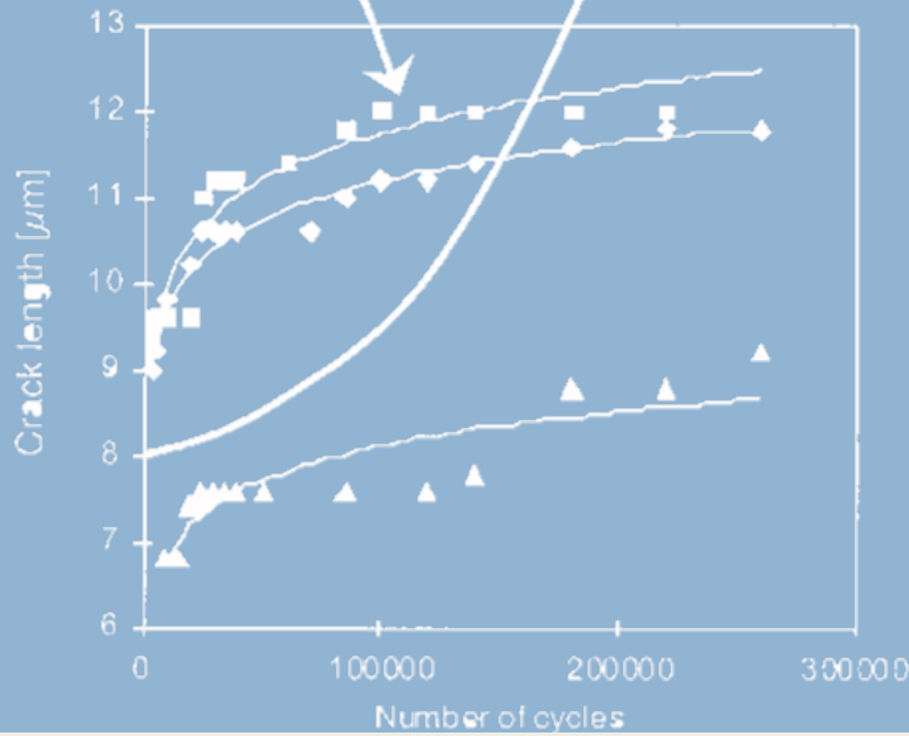


10.5 million cycles

Fibre-bridged cracking in CF/epoxy

Crack retardation

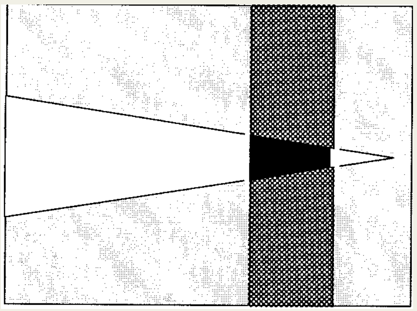
Paris type crack propagation

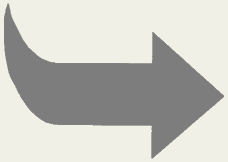


Transition in Fatigue mechanisms – propagation or termination

- **Region II**

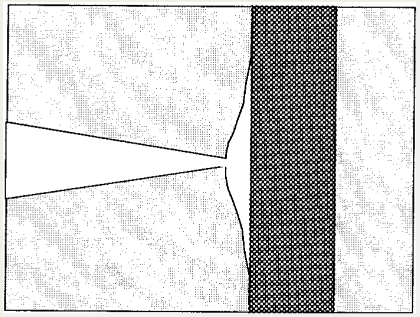
  Propagation of fibre bridged crack





- **Region III**

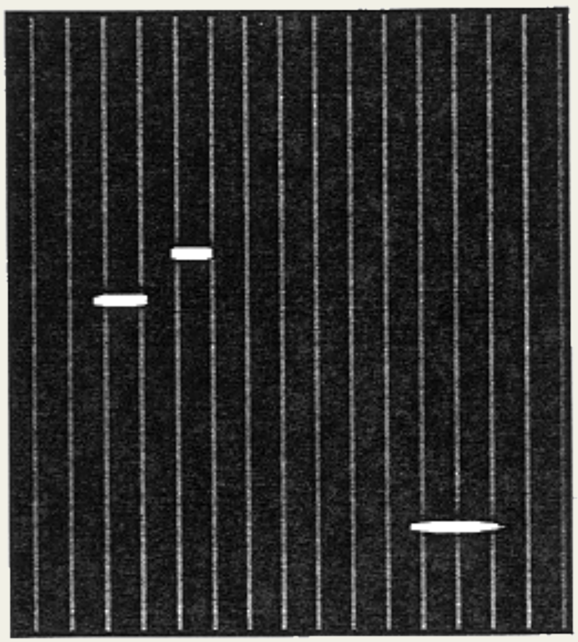
  Termination of crack growth by debonding



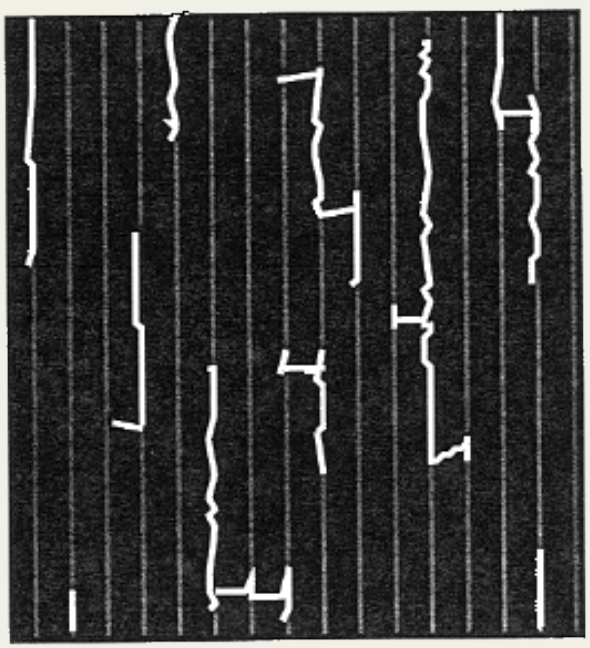
Fatigue damage mechanism

Epoxy vs. PEEK matrix

CF/epoxy

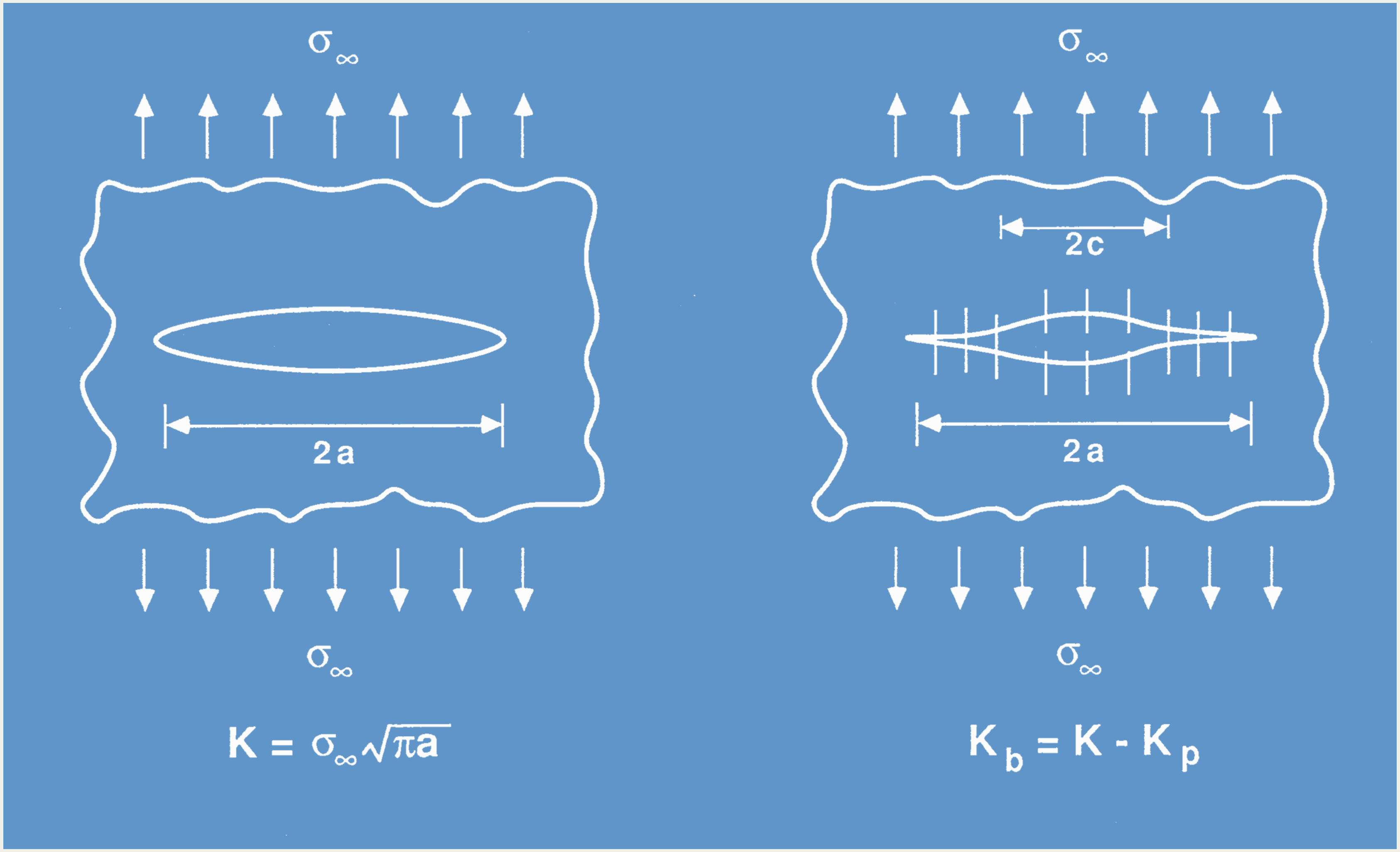


CF/PEEK



FIBER-BRIDGED CRACK

Stress Intensity Factor



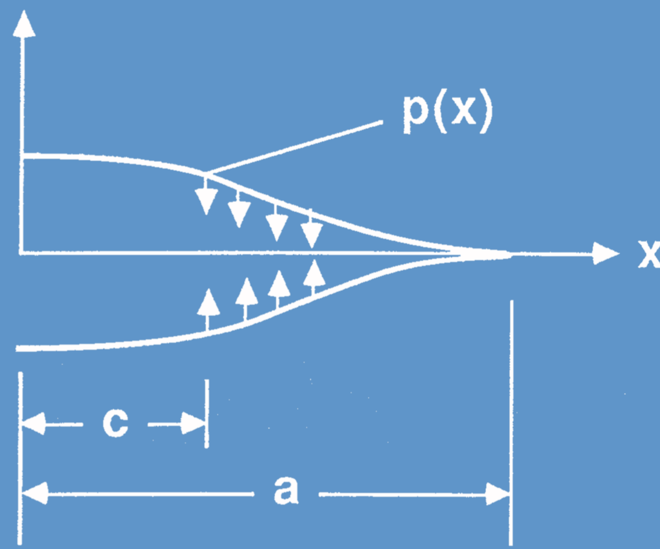
FIBER-BRIDGED CRACK

Stress Intensity Factor:

$$K_b = K - K_p$$

$$K = \sigma_\infty \sqrt{\pi a}$$

$$K_p = 2\sqrt{\frac{a}{\pi}} \int_c^a \frac{p(x)}{\sqrt{a^2 - x^2}}\, dx$$



Cyclic Stress:

$$\Delta K_b = \Delta K - \Delta K_p$$

$$= \Delta\sigma_\infty \sqrt{\pi a} - 2\sqrt{\frac{a}{\pi}} \int_c^a \frac{\Delta p(x) d(x)}{\sqrt{a^2 - x^2}}$$

FIBER-BRIDGED CRACK

Effective Crack Length :

$$\Delta K_b = \Delta K \left(1 - \frac{\Delta K_p}{\Delta K}\right)$$

$$\frac{\Delta K_p}{\Delta K} = \text{constant, if } p(x) = p_o, c<x<a$$

$$\text{or if } p(x) = p_o \text{ (a-x3. /a-c)}, 0<x<a$$

For constant $\frac{\Delta K_p}{\Delta K}$ **,**

$$\Delta K_b = \Delta\sigma_\infty \sqrt{\pi(a-d)}\text{ , } d = \text{constant}$$

Define Effective Crack Length :

$$a_e = a - d$$

FIBER-BRIDGED CRACK

Crack Growth Rate :

$$da/dN = C\,(\Delta K_b)^n$$

$$= C\,(\Delta\sigma_\infty)^n\,\pi^{n/2}\,(a-d)^{n/2}$$

Integrating :

$$N_f\,(\Delta\sigma_\infty)^n = B \qquad \text{where } B = C^{-1}\,\pi^{-n/2}\int_{a_0}^{a_c}(a-d)^{-n/2}\,da$$

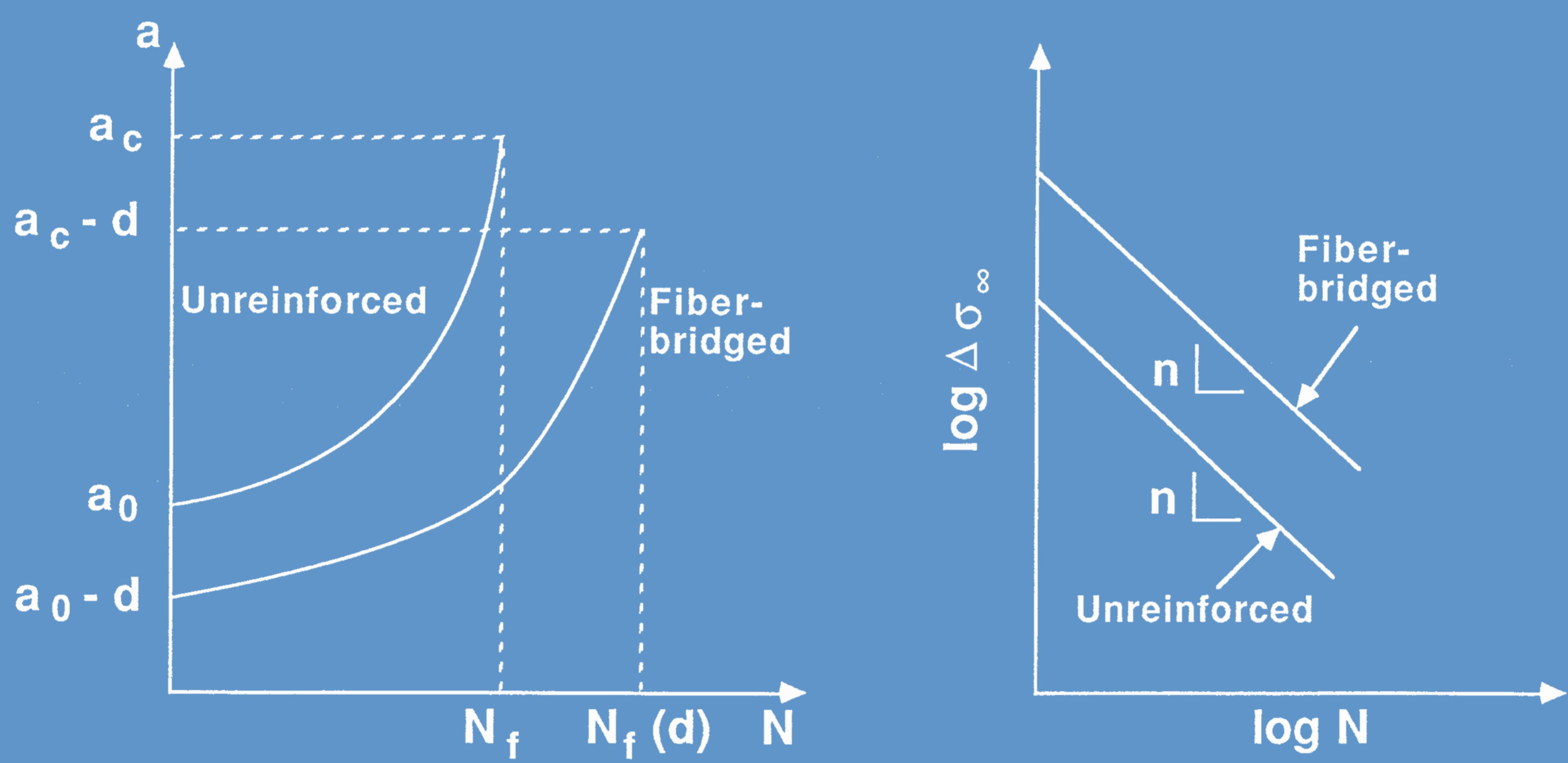
For unreinforced crack :

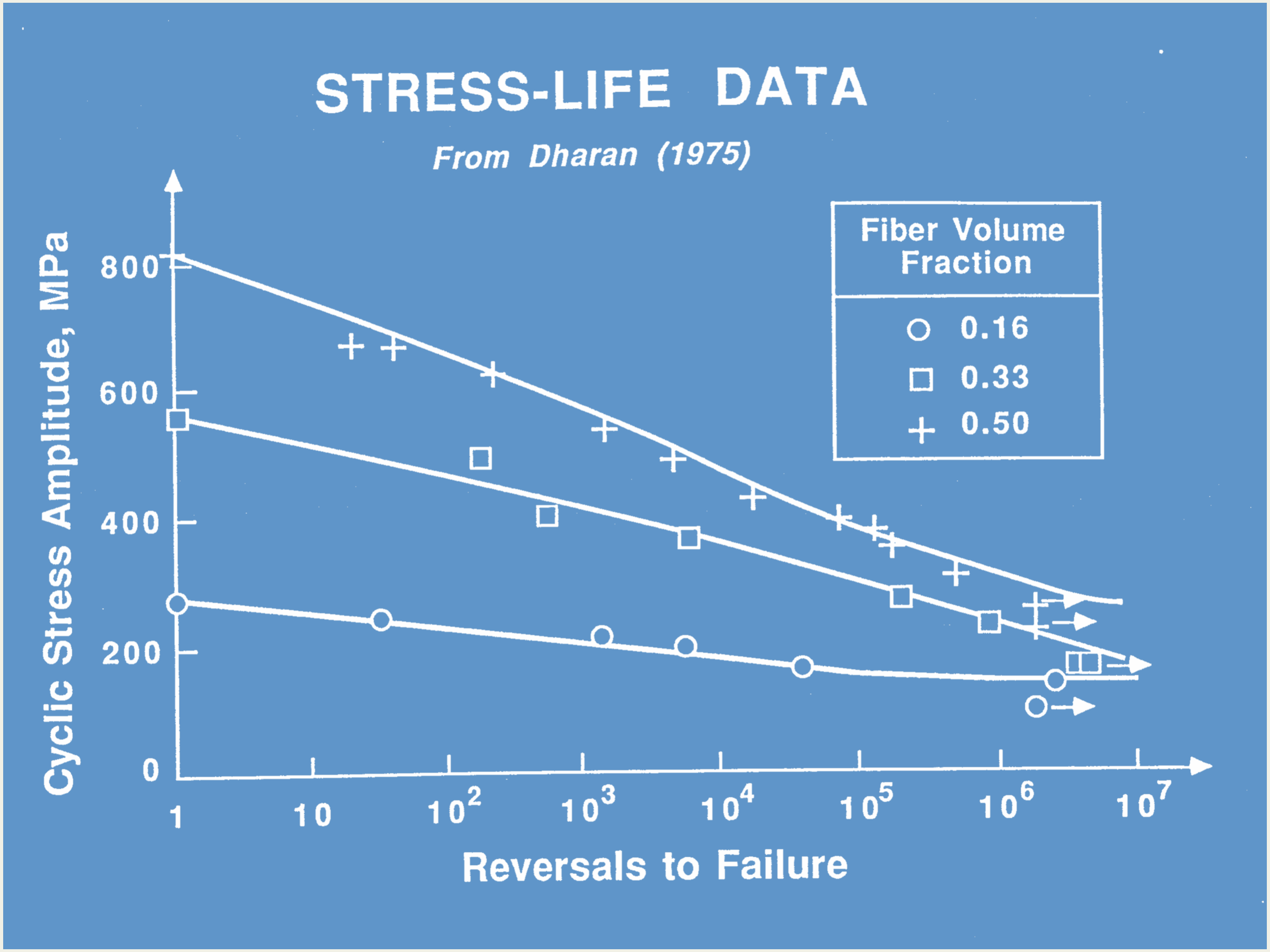
$$N_f\,(\Delta\sigma_\infty)^n = A \qquad \text{where } A = C^{-1}\,\pi^{-n/2}\int_{a_0}^{a_c}a^{-n/2}\,da$$

$$\frac{B}{A} = \frac{\int_{a_0}^{a_c}(a-d)^{-n/2}\,da}{\int_{a_0}^{a_c}a^{-n/2}\,da}$$

FIBER-BRIDGED CRACK

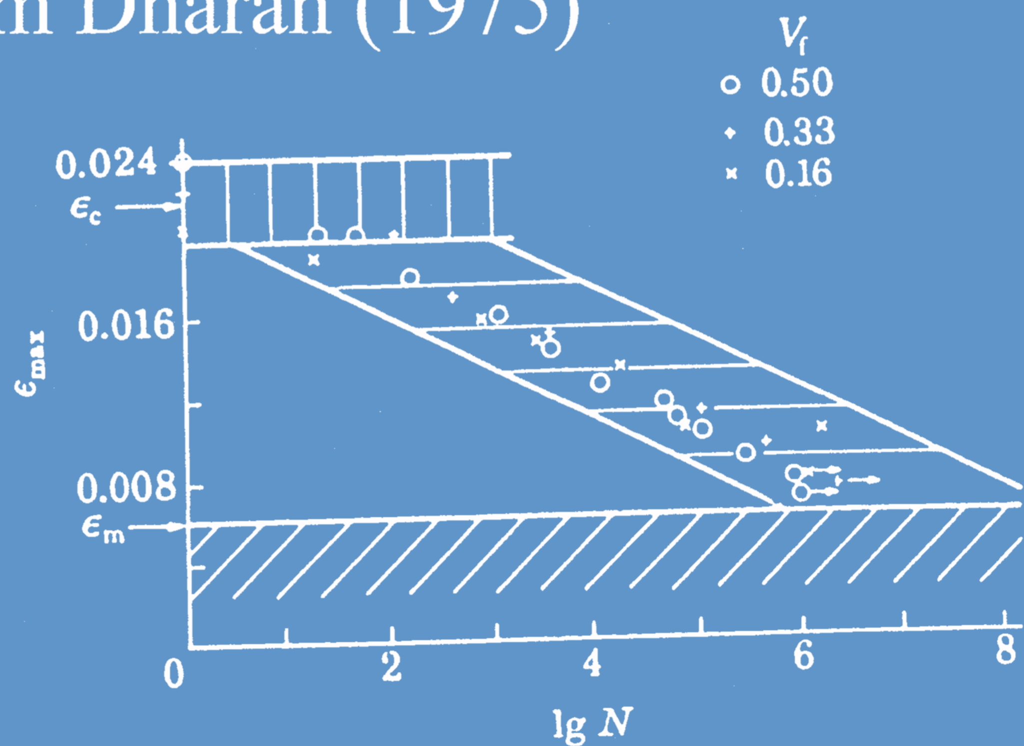
Fatigue Life Delay




STRESS-LIFE DATA
From Dharan (1975)
Fiber Volume Fraction
0.16
0.33
0.50
Cyclic Stress Amplitude, MPa
800
600
400
200
0
1
10
10^2
10^3
10^4
10^5
10^6
10^7
Reversals to Failure

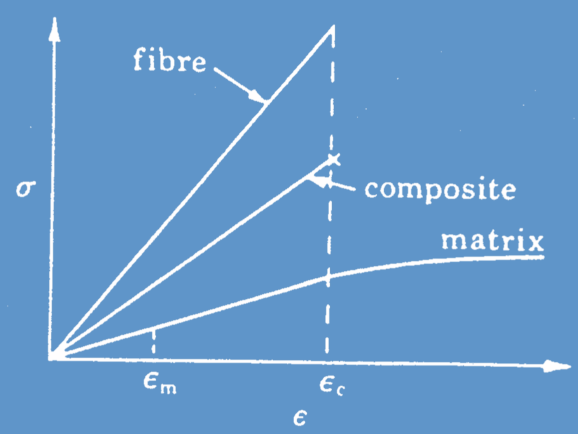
Fatigue Life Diagram
Unidirectional Glass-Epoxy Loaded Parallel to Fibers

- Data from Dharan (1975)

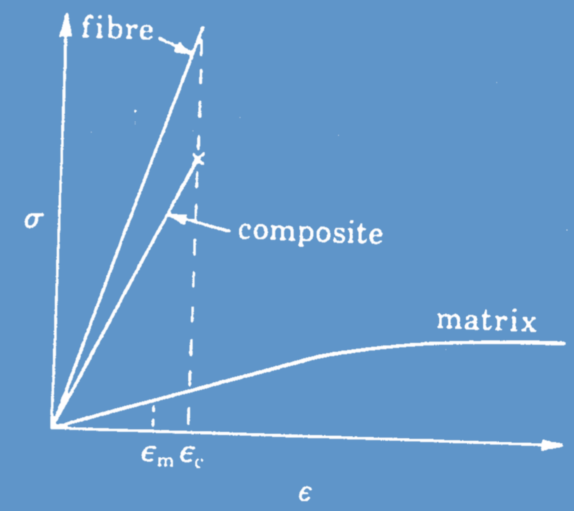


Effect of Fiber Stiffness on Fatigue of Unidirectional Composites

Low Stiffness Fibers



High Stiffness Fibers

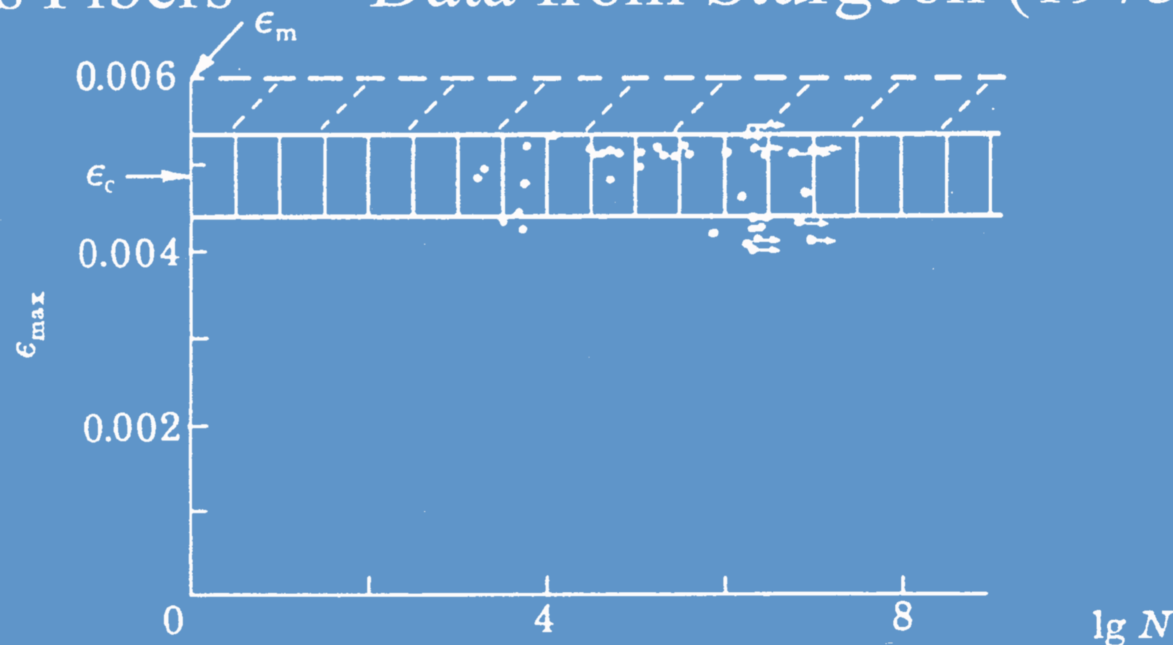


ε_c = composite failure strain

ε_m = matrix fatigue limit

Fatigue Life Diagram
Unidirectional Type I Carbon-Epoxy

High Stiffness Fibers   Data from Sturgeon (1973)



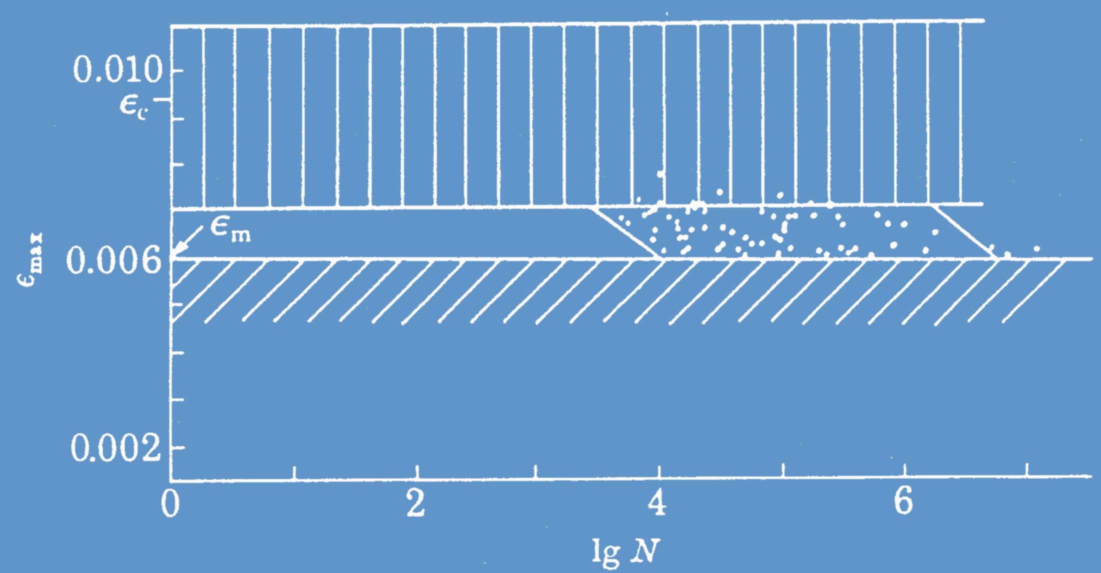
Note: Non-progressive fiber breakage only.

No Fatigue!

Fatigue Life Diagram
Unidirectional Type II Carbon-Epoxy

Medium Stiffness Fibers

Data from Awerbuch & Hahn (1973)

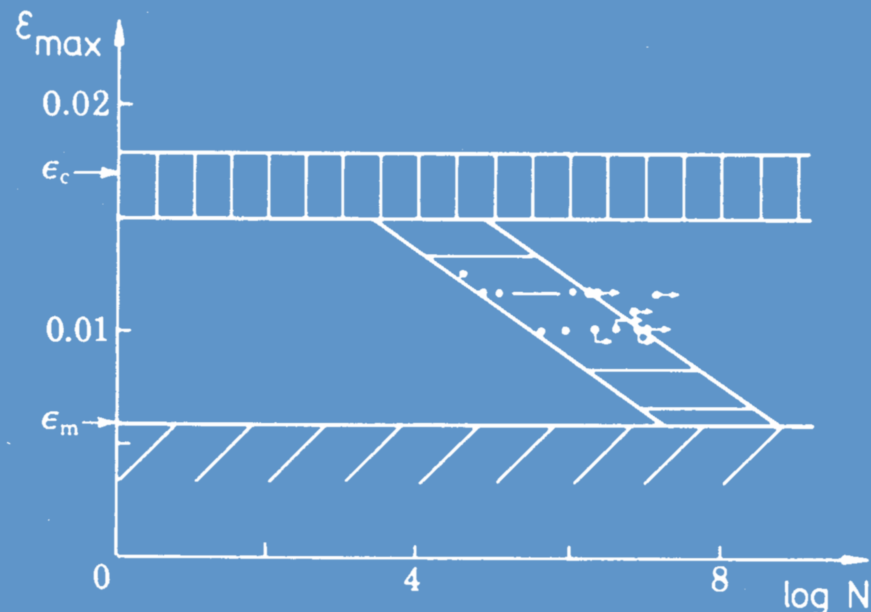


Note: Narrow range of strain where fatigue occurs.

Fatigue Life Diagram
Unidirectional Type III Carbon-Epoxy

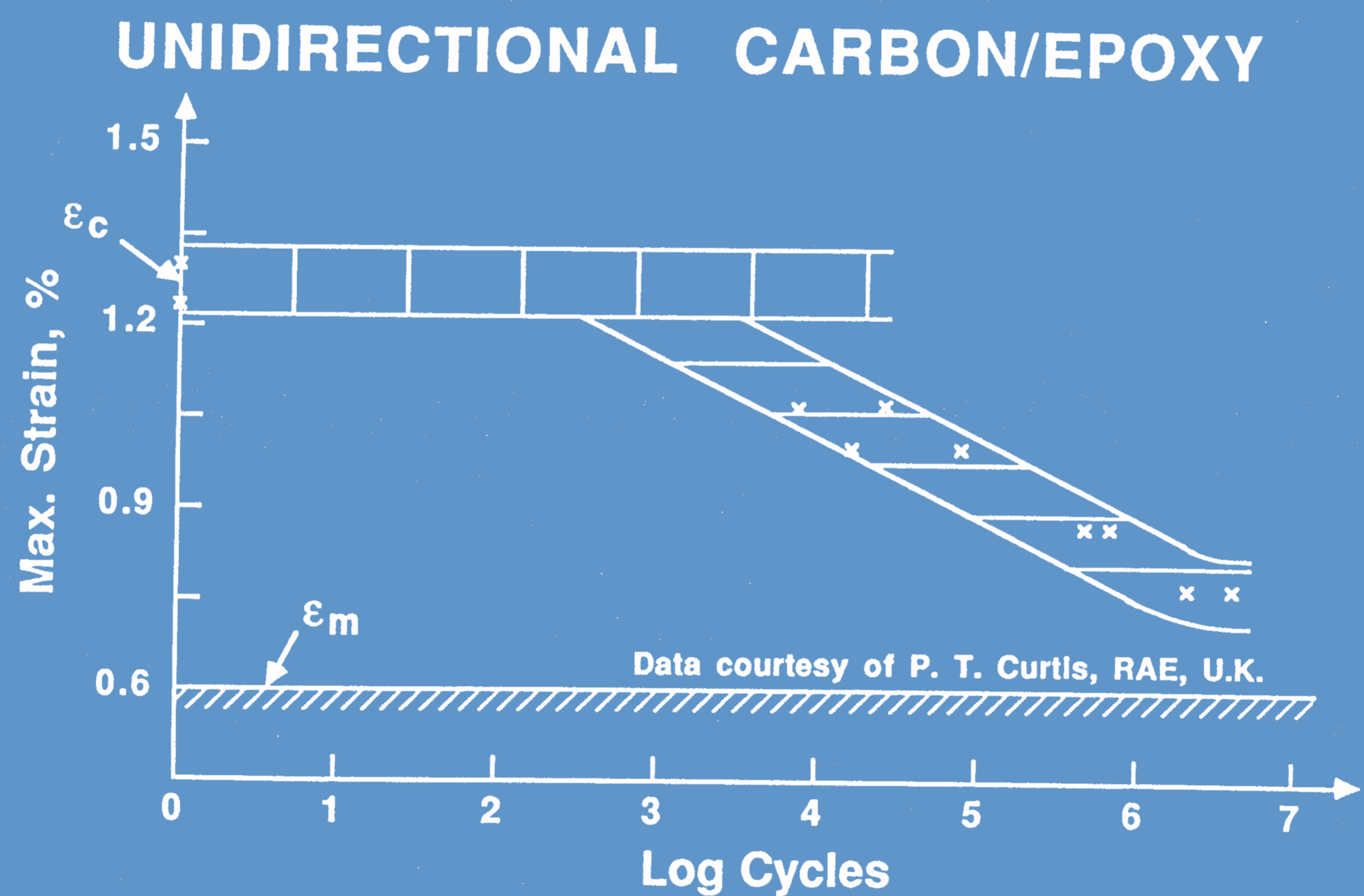
Low Stiffness Fibers

Data from Sturgeon (1975)

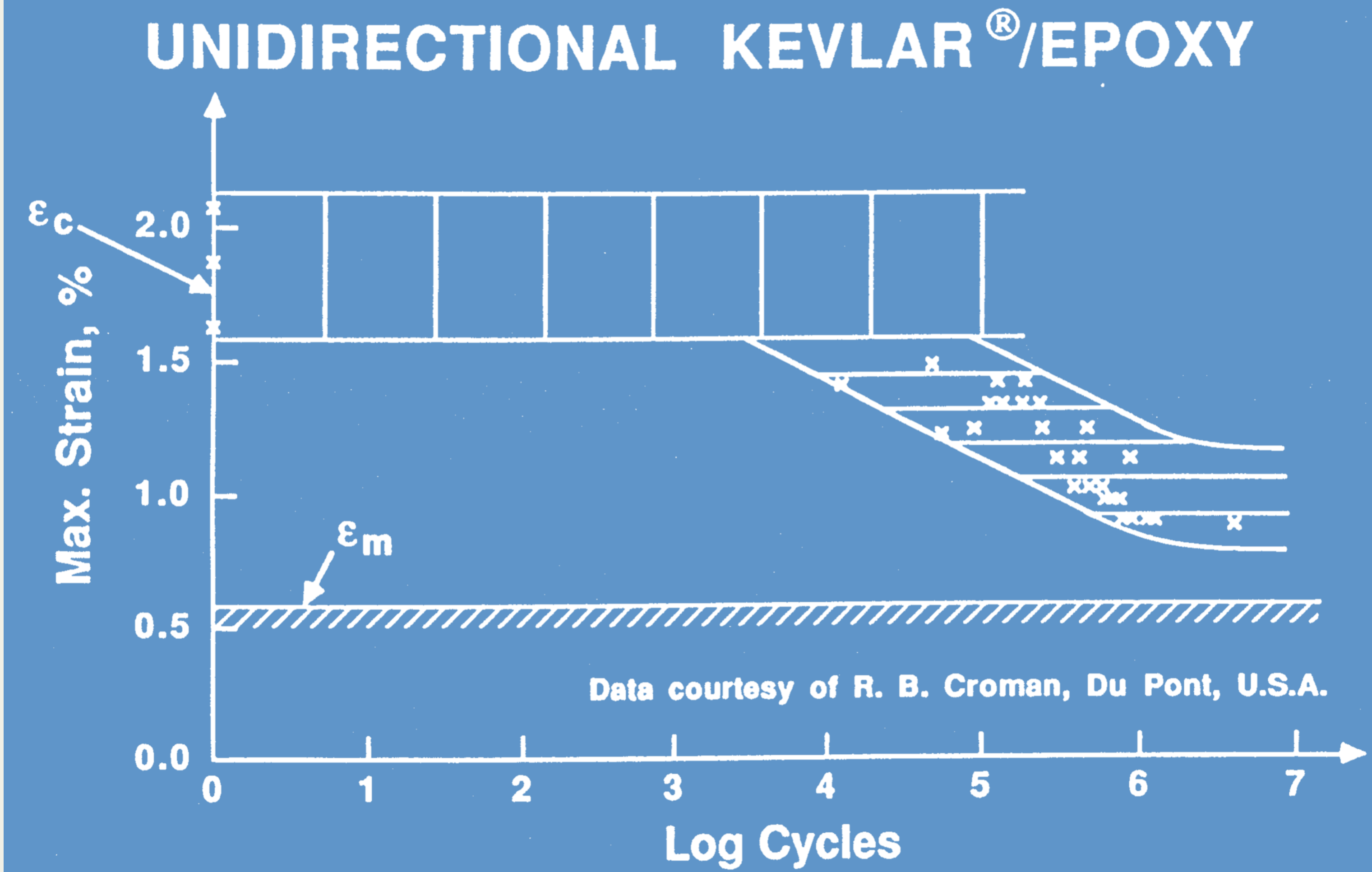


Note: Wide range of strain where fatigue occurs.

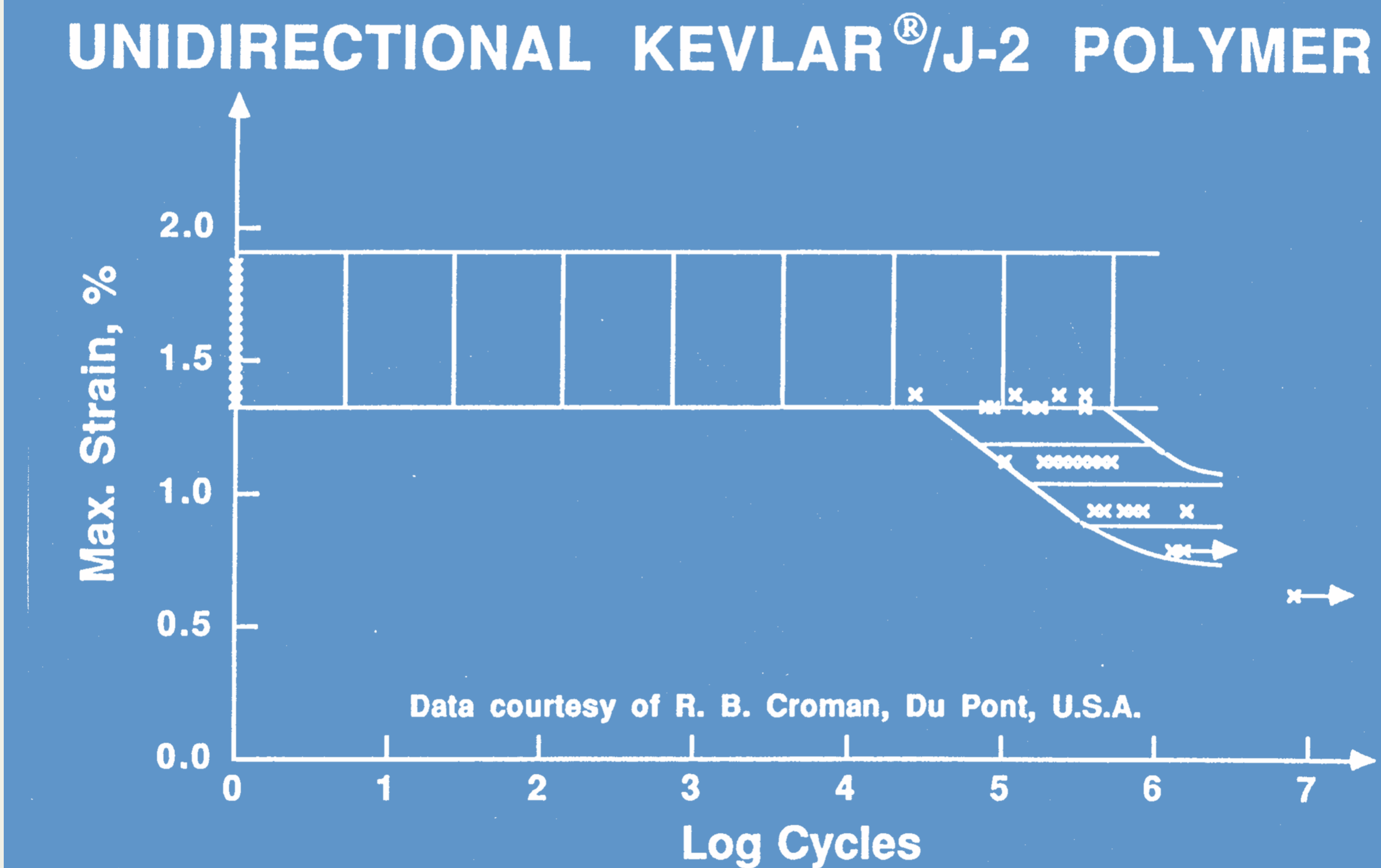
Fatigue Life Diagram



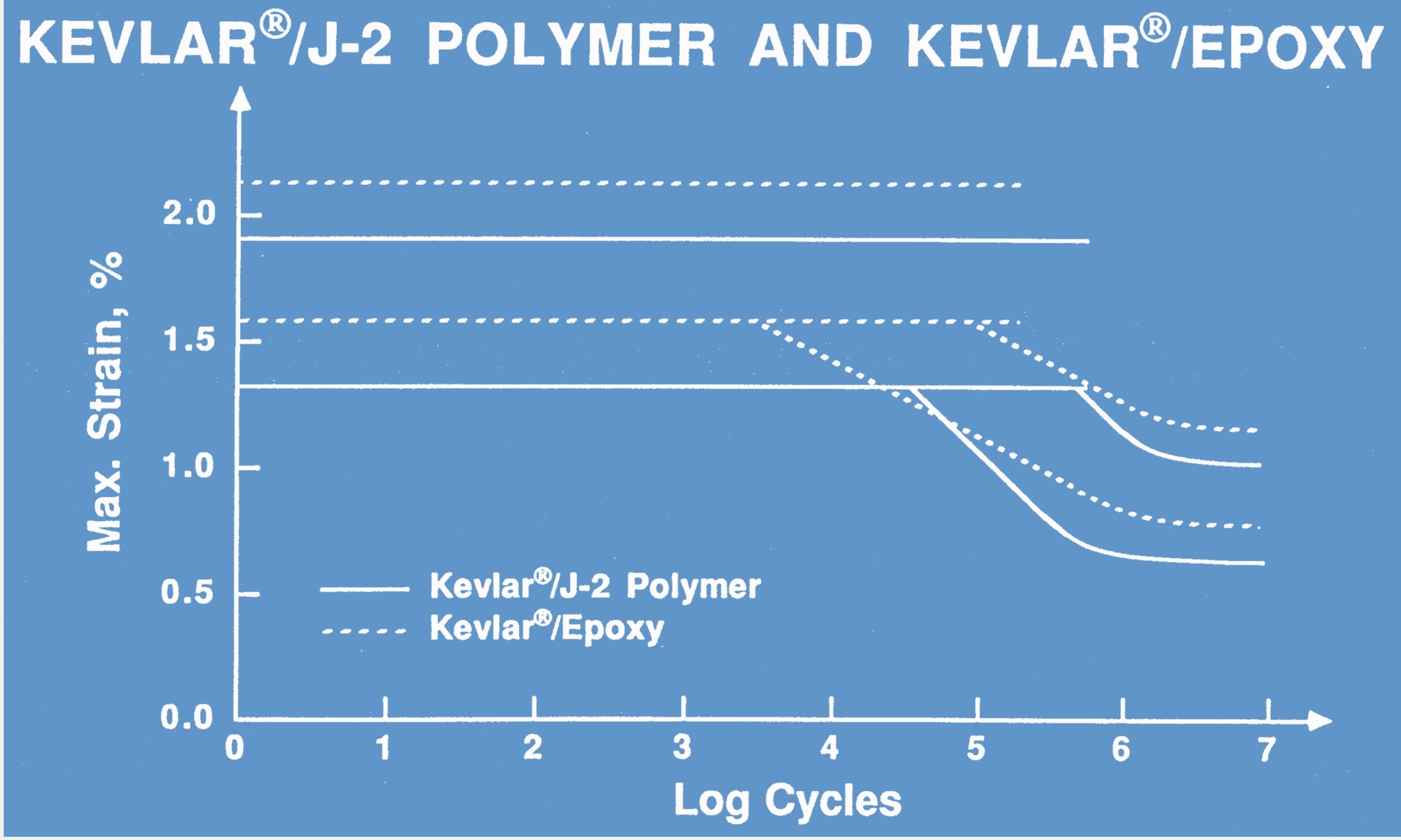
Fatigue Life Diagram



Fatigue Life Diagram

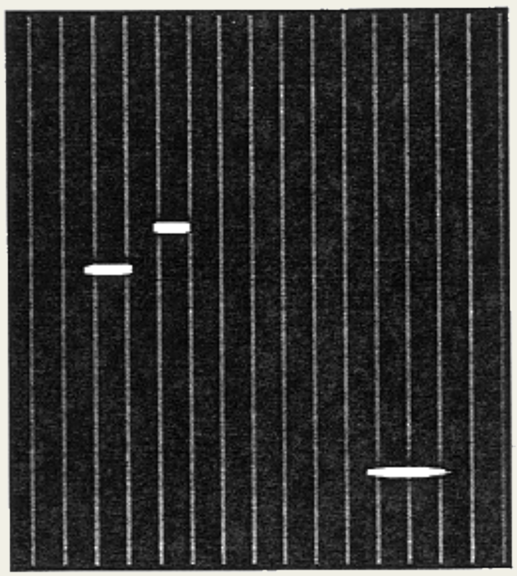


Fatigue Life Diagram

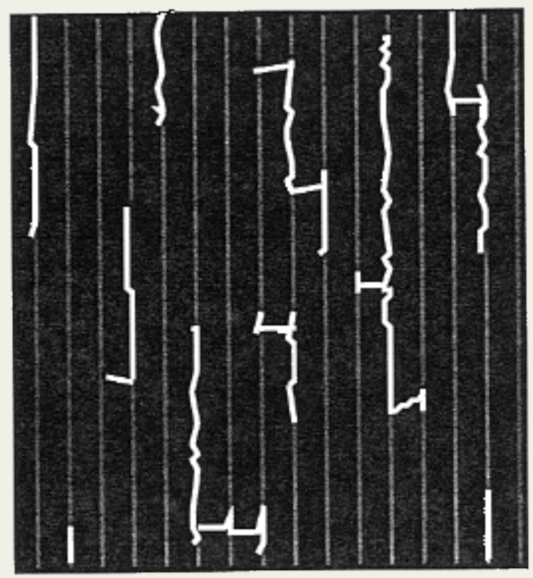


Schematic difference in fatigue damage

CF/epoxy

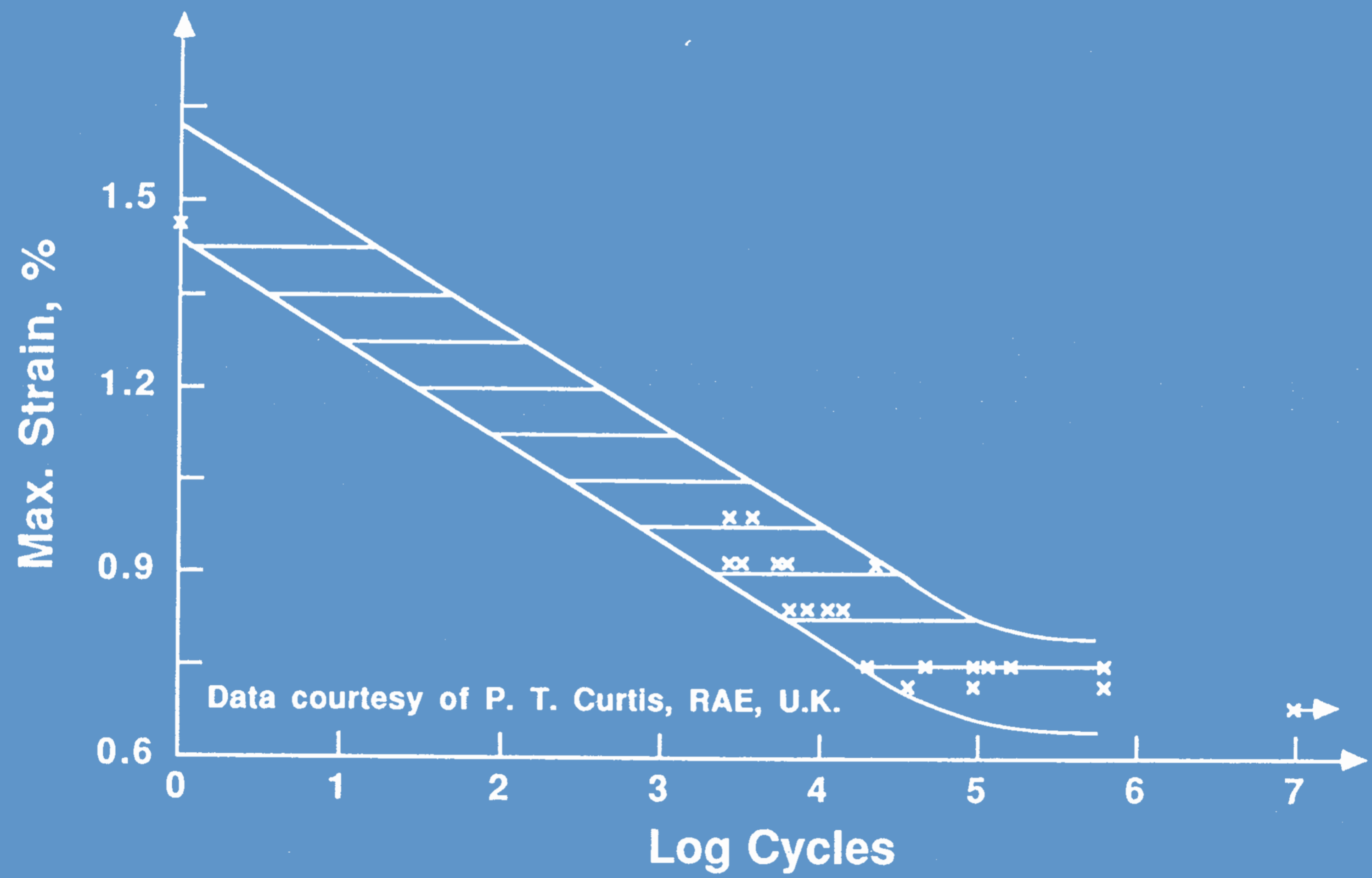


CF/PEEK

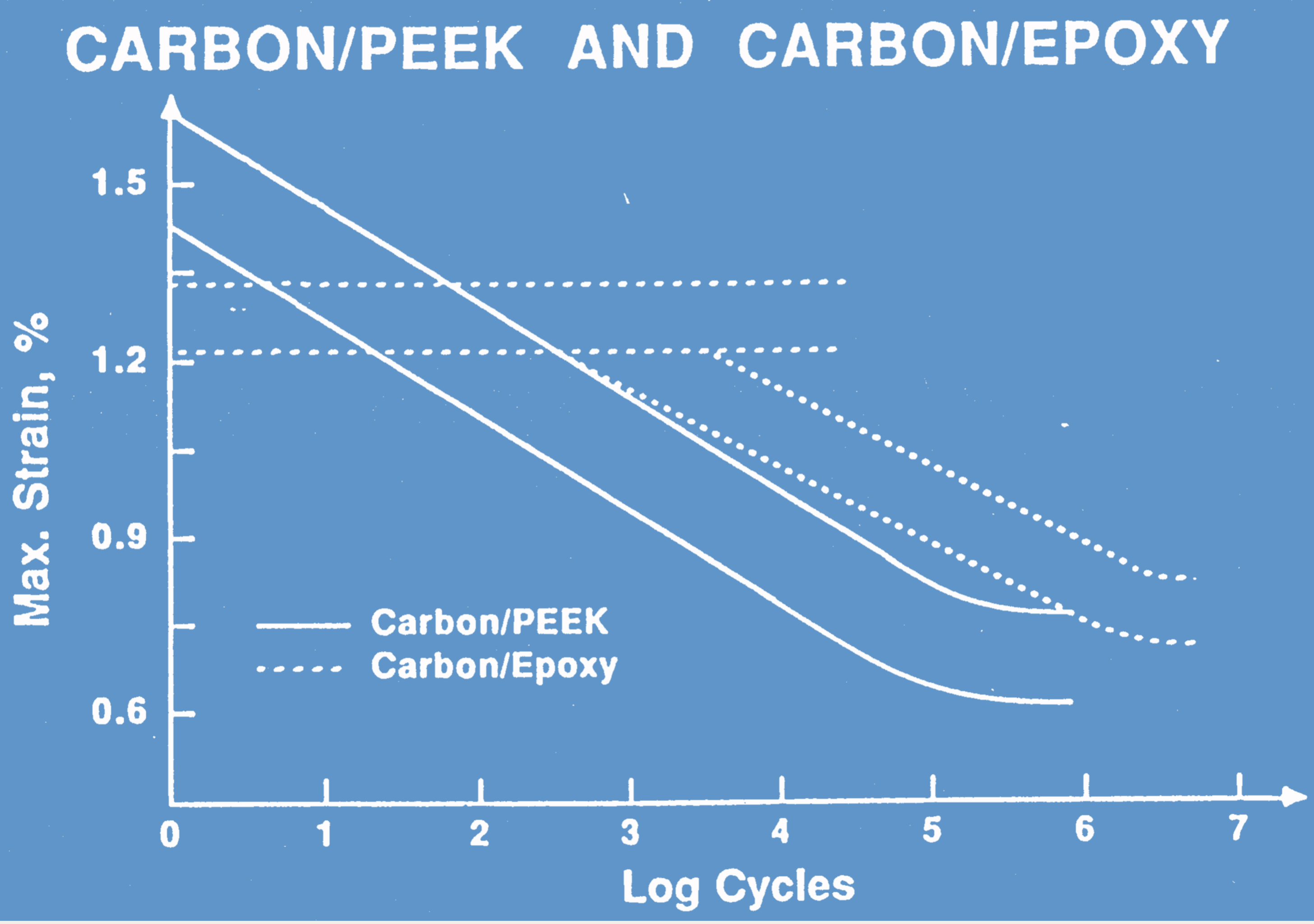


Fatigue Life Diagram

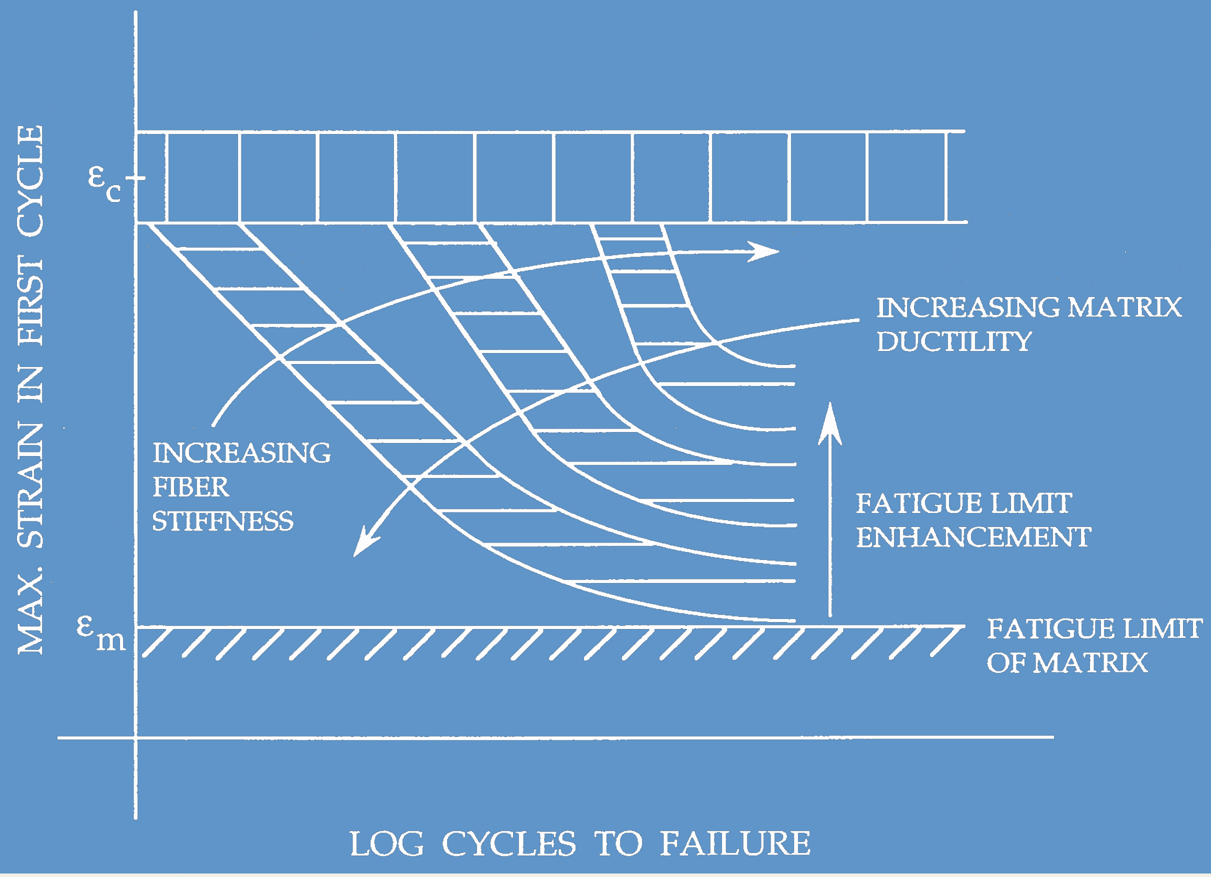
UNIDIRECTIONAL CARBON/PEEK



Fatigue Life Diagram



Trends in Fatigue Life Diagram due to Constituent Properties



Basics of fatigue

- If in the first application of load, events of damage occur, then in subsequent load applications damage progression is possible.

- Failure occurs when accumulated damage reaches a critical state (defined as loss of functionality).

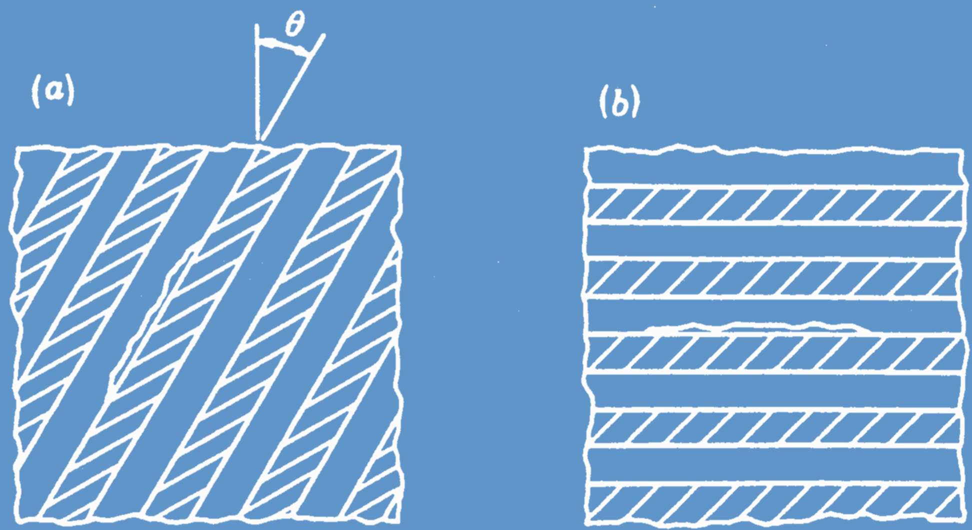
Basics of fatigue limit

- Fatigue limit is the MAXIMUM LOADING STATE, below which one of the following conditions is satisfied.

A) No damage event (causing energy dissipation) occurs during the first application of load.

B) Insufficient damage progression occurs to reach failure in a large number (e.g. 10^7) cycles.

Fatigue Damage Mechanisms
Off-Axis Loading of Unidirectional Composites

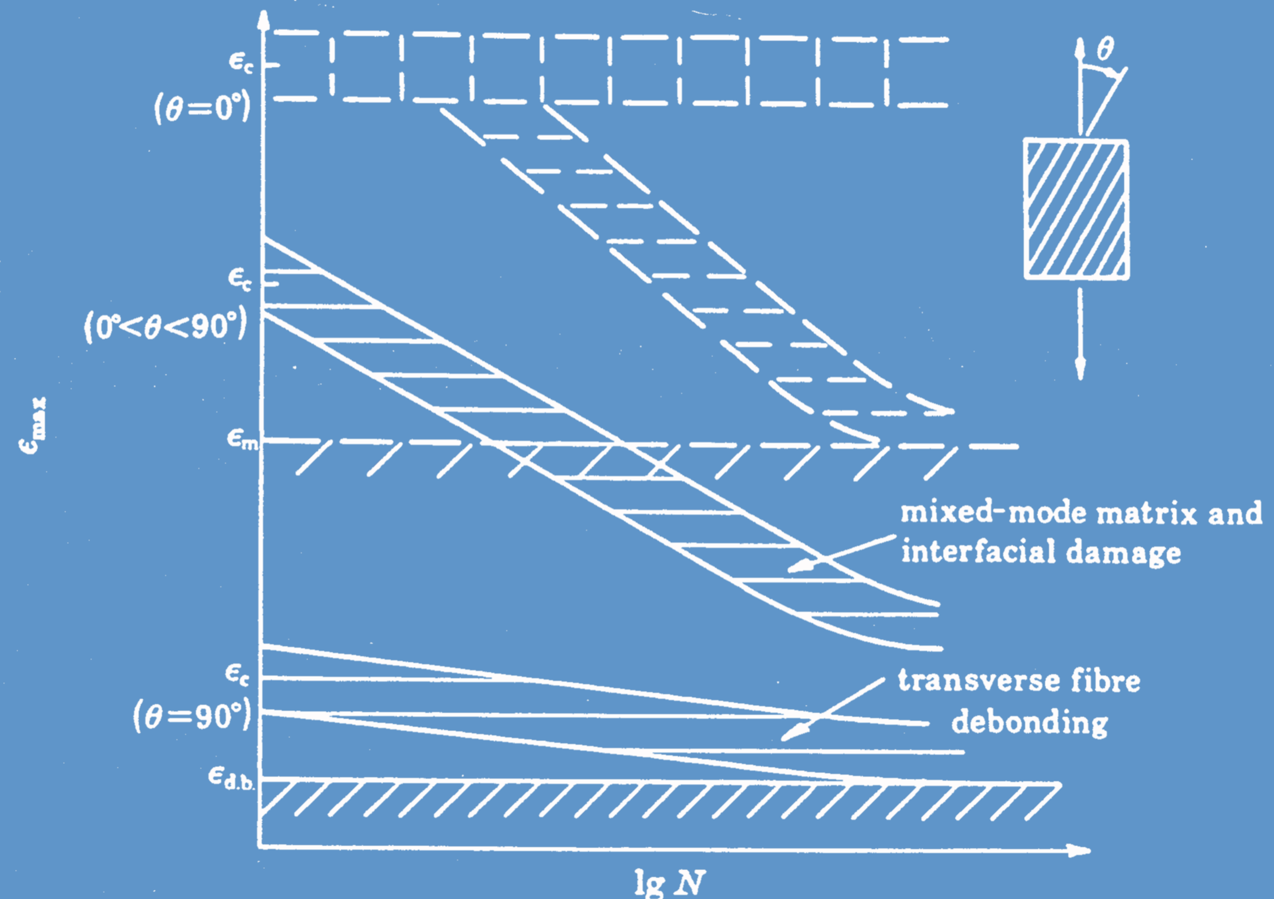


a) $0 < \theta < 90$ Mixed-mode (opening/sliding) cracking

b) $\theta = 90$ Transverse Fiber Debonding

Fatigue Life Diagram

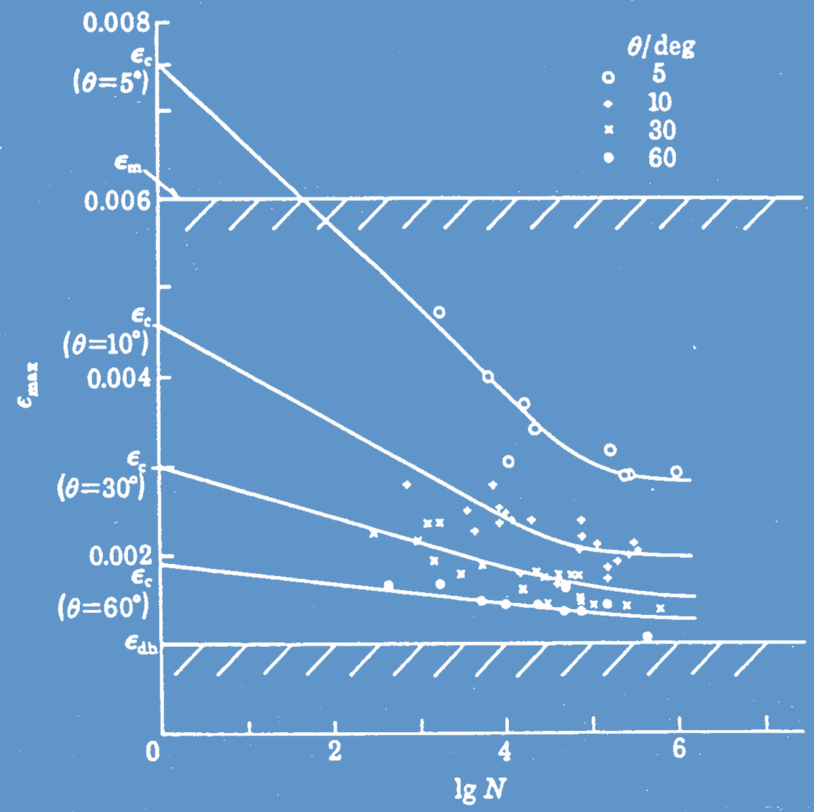
Off-Axis Loading of Unidirectional Composites



Fatigue Life Diagram

Off-Axis Loading of Unidirectional Composites

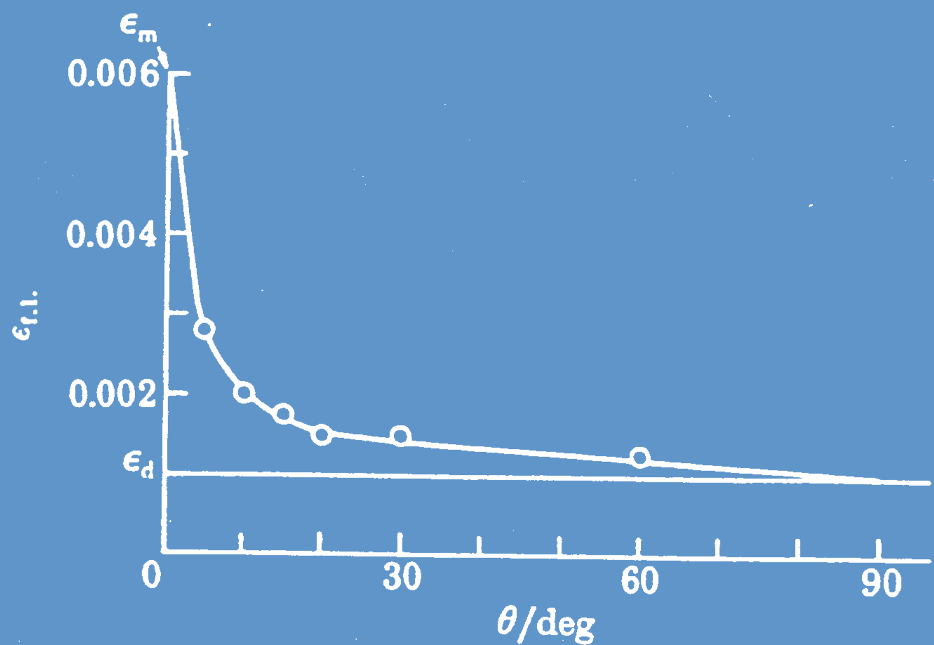
Glass-Epoxy   Data From Hashin & Rotem (1973)



Fatigue Limit Behavior

Off-Axis Loading of Unidirectional Composites

Glass-Epoxy   Data From Hashin & Rotem (1973)

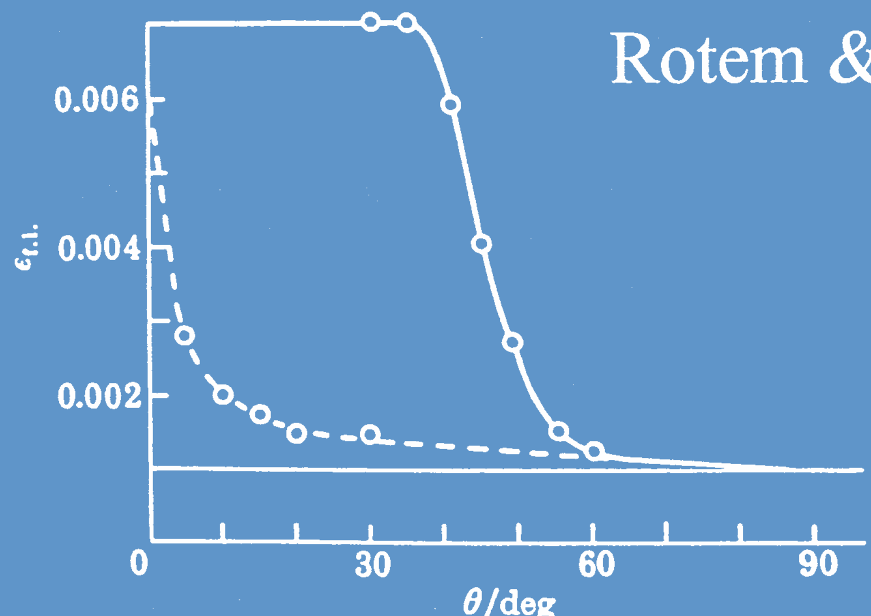


Fatigue Limit Behavior

Off-Axis Loading of Unidirectional Composites
On-Axis Loading of Angle Ply Laminates

Glass-Epoxy Data From Hashin & Rotem (1973)

Rotem & Hashin (1976)

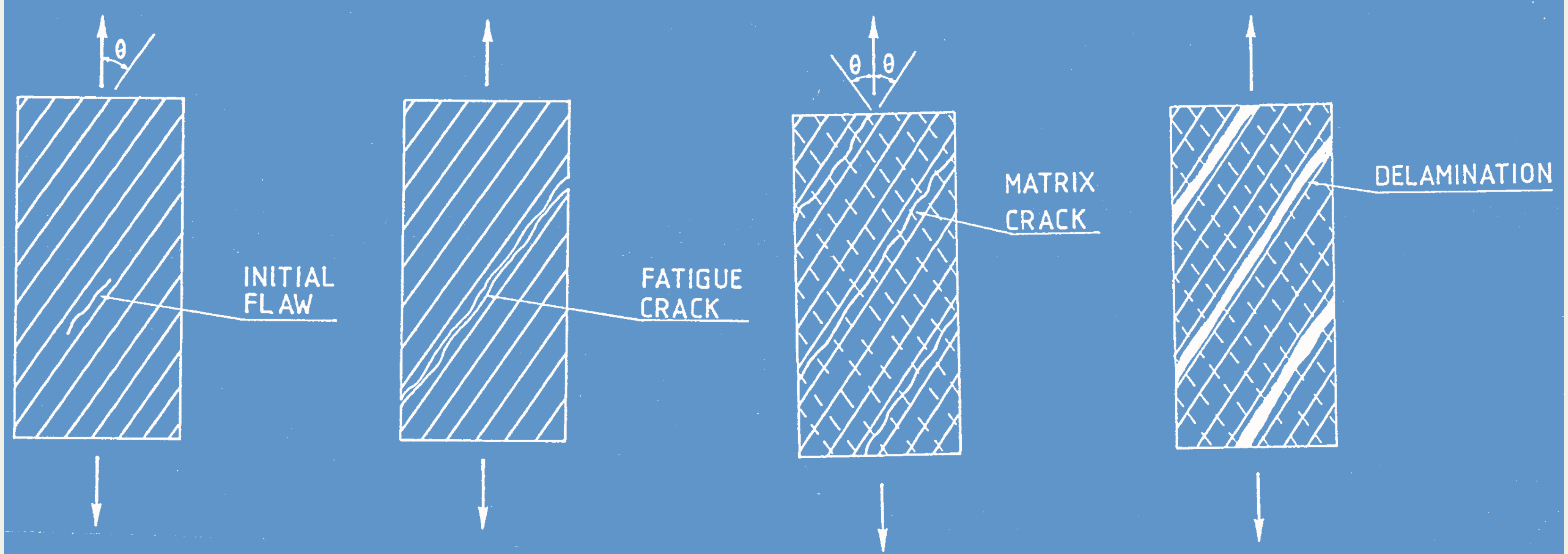


Dashed line: Off-axis loading of UD composite

Fatigue Damage Mechanisms

Off-Axis Loading of Unidirectional Composites

On-axis Loading of Angle Ply Laminate

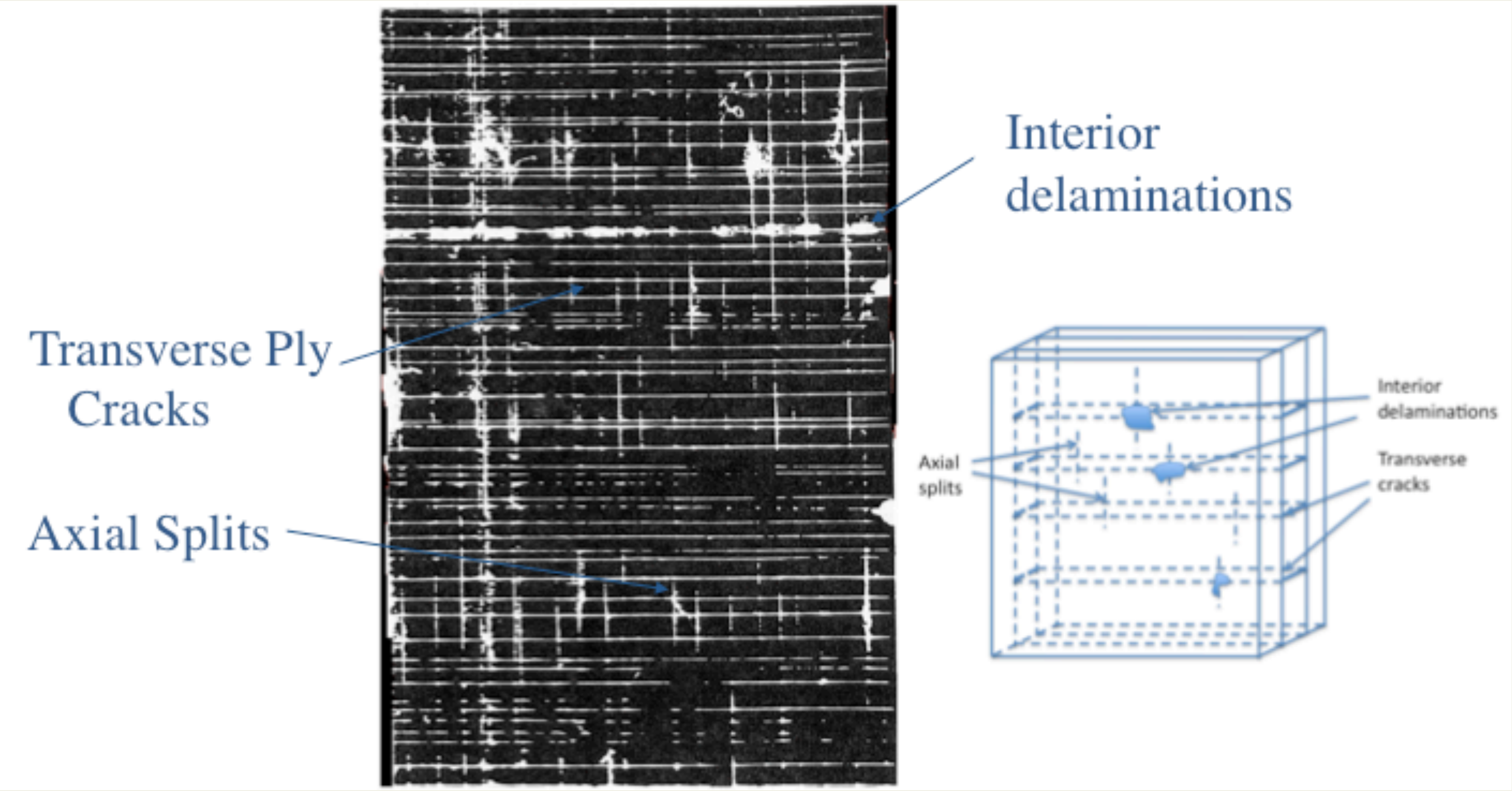


UD Composite

Angle Ply Laminate

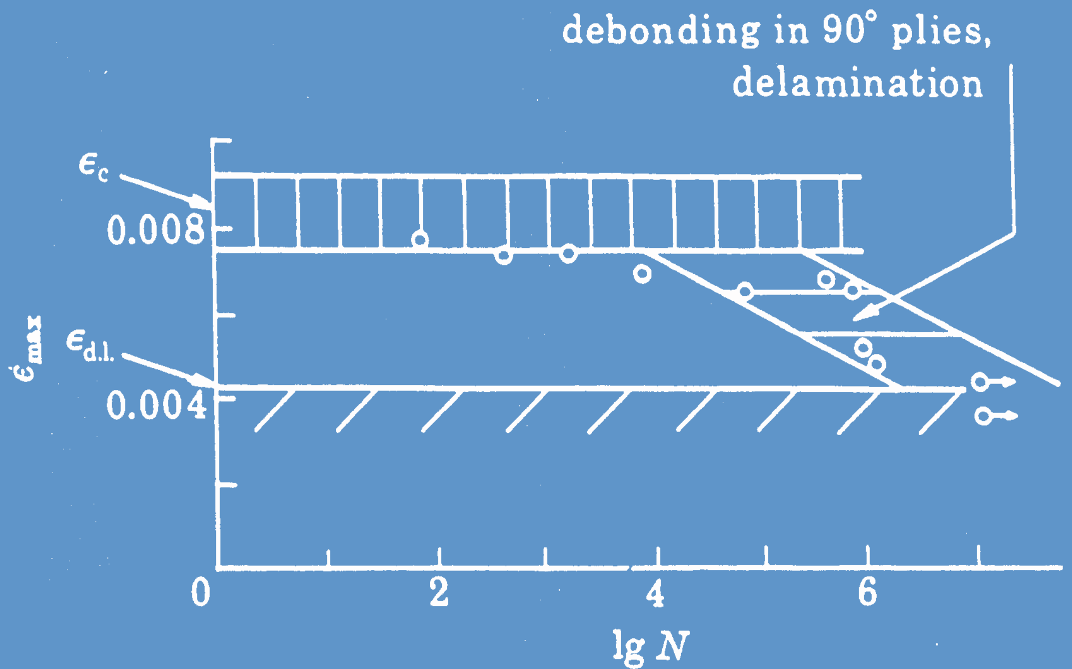
CROSS PLY LAMINATES

FATIGUE DAMAGE MECHANISMS



SOURCE: JAMISON et al., ASTM STP 836, 1984.

FATIGUE LIFE DIAGRAM OF CROSS PLY LAMINATES



DATA OF GRAPHITE–EPOXY FROM GRIMES (1977)

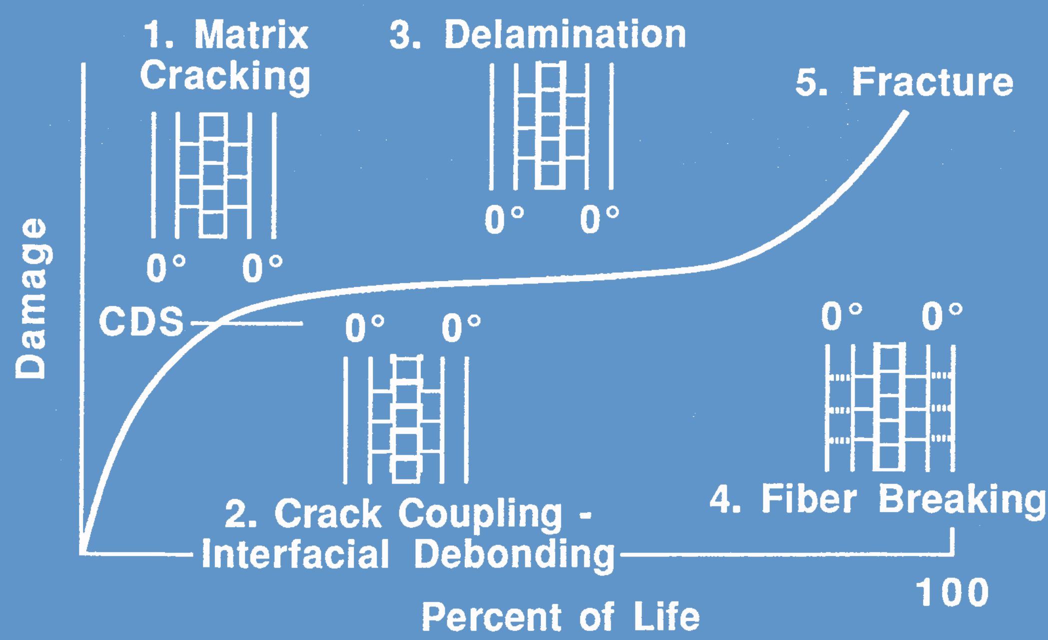
FEATURES OF FATIGUE LIFE DIAGRAM:

1. NONPROGRESSIVE FIBER BREAKAGE PROCESS IS PRESENT
2. FATIGUE LIMIT IS GIVEN BY STRAIN TO TRANSVERSE CRACKING LEADING TO DELAMINATION

COMPOSITE LAMINATES (POLYMERIC MATRIX)

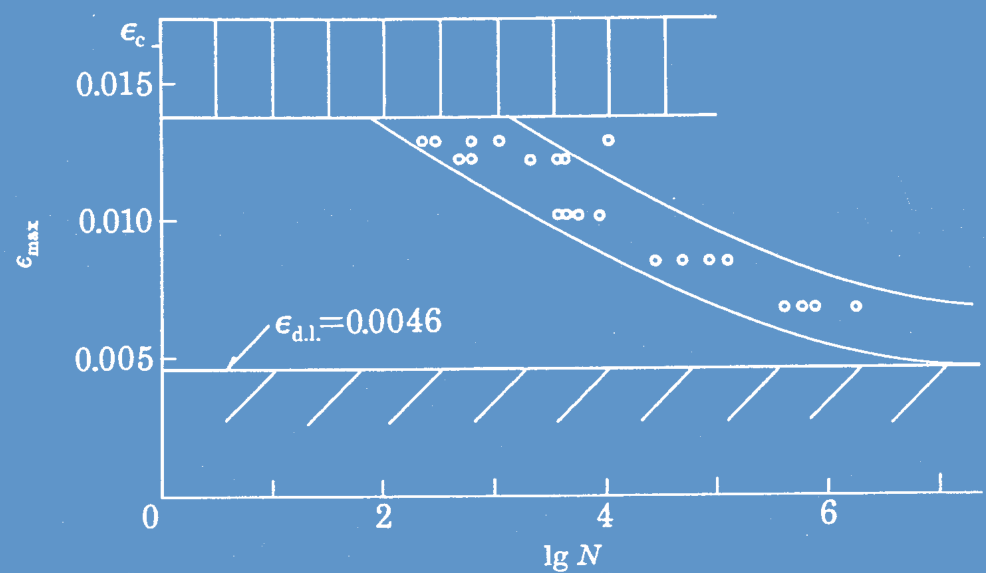
Dominant Damage Modes:

- Intralaminar Cracking (pre-CDS)
- Interlaminar Cracking (post-CDS)



Fatigue Damage Mechanisms

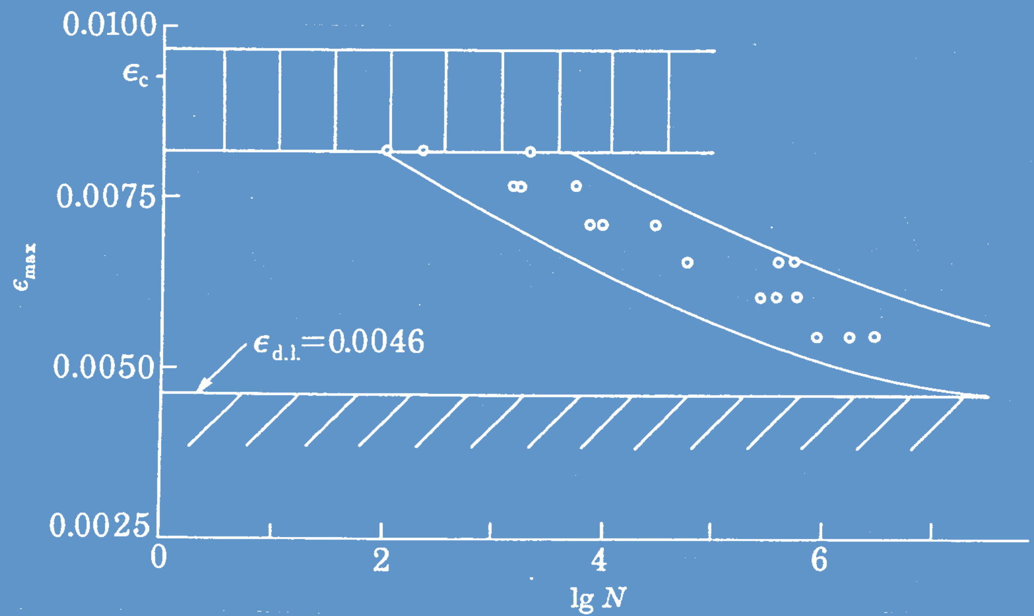
General Laminates



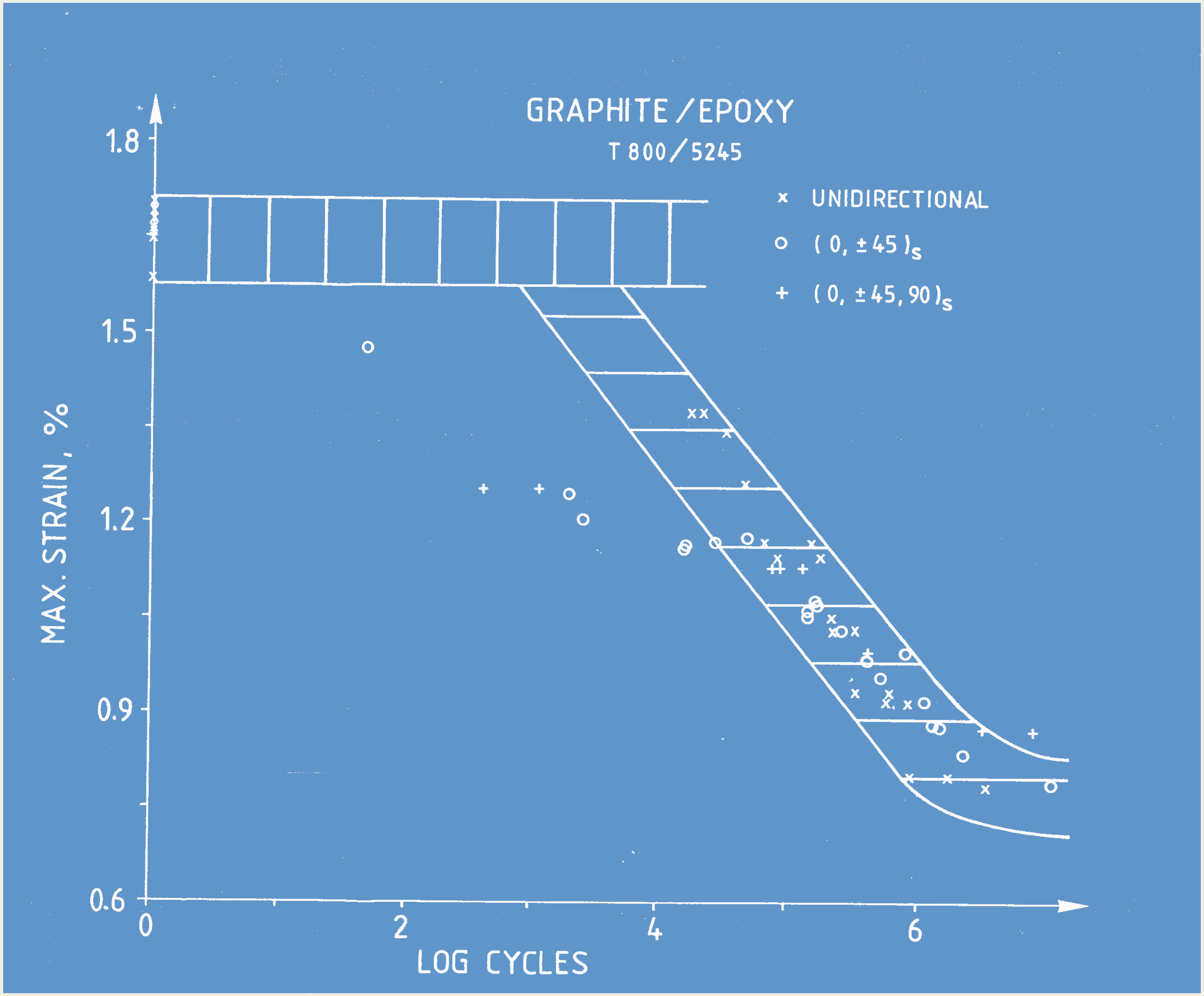
Data: Glass-Epoxy $(0, \pm 45, 90)_s$ Hahn & Kim (1976)

Fatigue Damage Mechanisms

General Laminates



Data: Carbon-Epoxy (0, 45, 90, -45$_2$, 90, 45, 0)$_s$ Ryder & Walker (1977)


GRAPHITE / EPOXY
T 800 / 5245
× UNIDIRECTIONAL
○ (0, ± 45)s
+ (0, ± 45, 90)s
MAX. STRAIN, %
1.8
1.5
1.2
0.9
0.6
0
2
4
6
LOG CYCLES

Summary

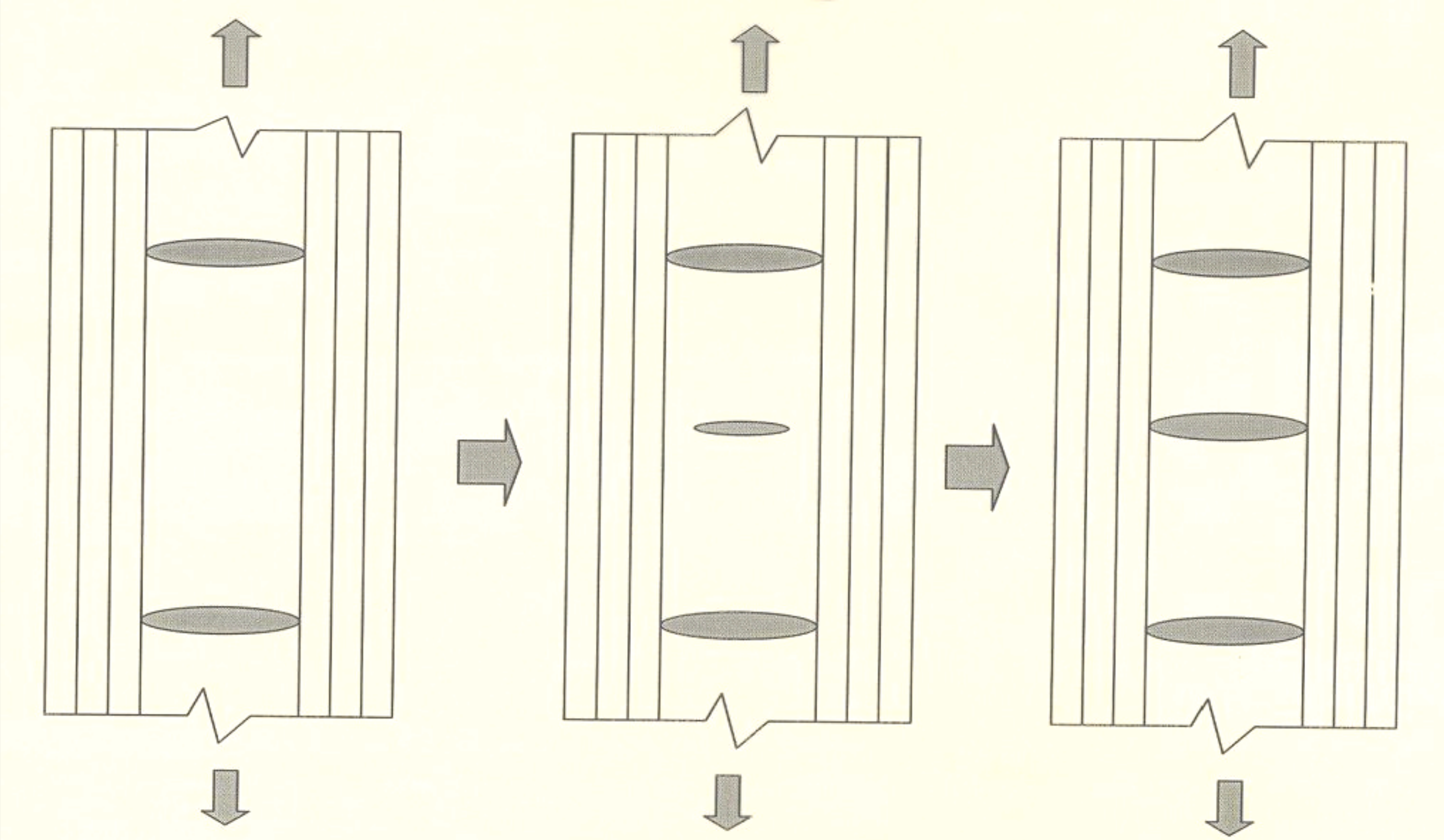
- Fatigue Life Diagrams provide a conceptual framework and systematic means for interpretation and assessment of the role of constituents in fatigue of composites

- These diagrams facilitate selection of fibers and matrix and devising of fiber architecture for desired fatigue properties.

- Ignoring Region I of fatigue behavior, which is often done, can lead to serious errors in life estimation, especially for high stiffness fiber composites.

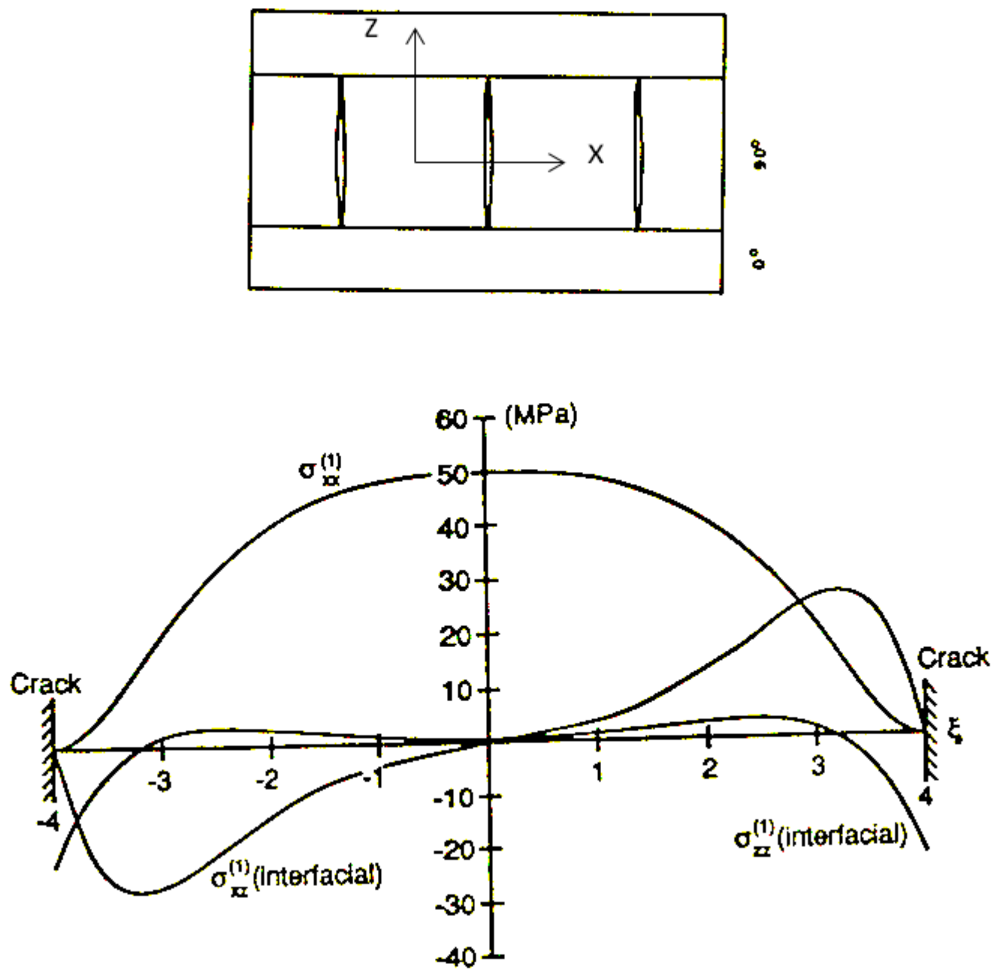
- A proper representation of fatigue limit is in strain – not stress – and it is a matrix governed property

Fatigue Life Prediction

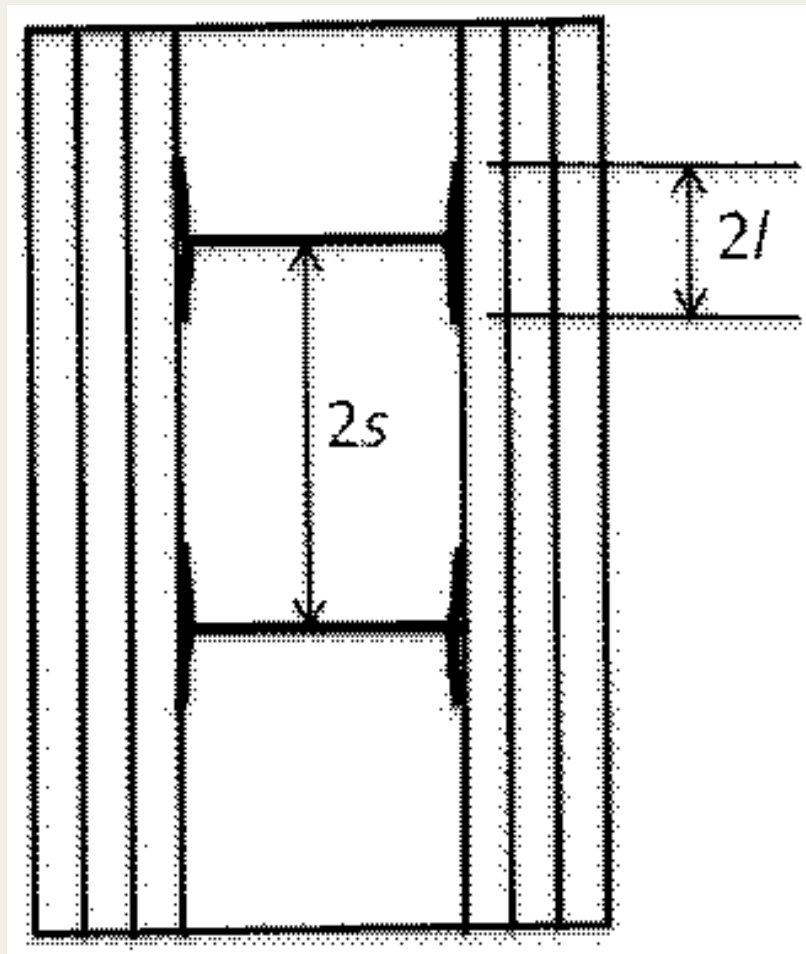


What makes a new crack appear between two pre-existing cracks?

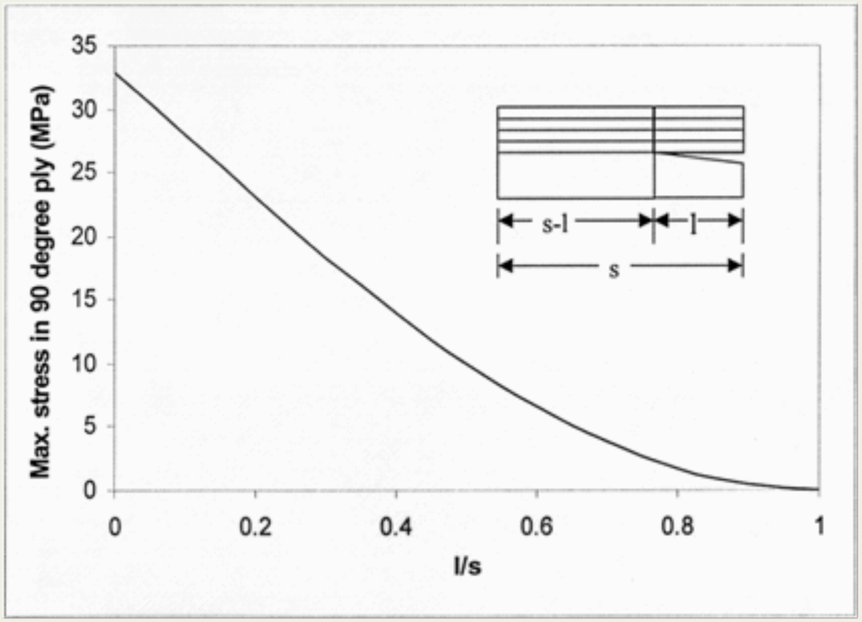
Stresses in 90-plies between pre-existing cracks in a cross ply laminate

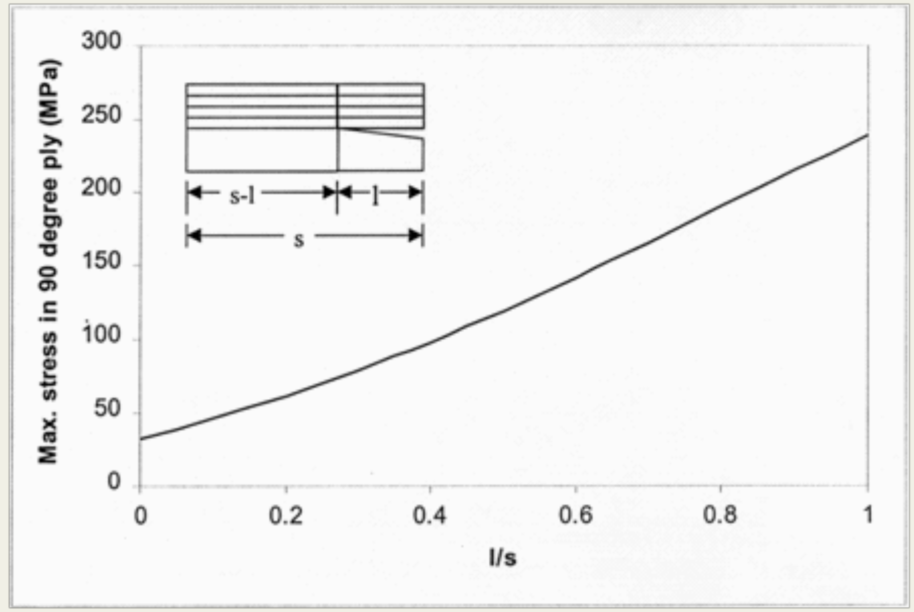


Irreversibility modeled as frictional sliding of delaminated surfaces



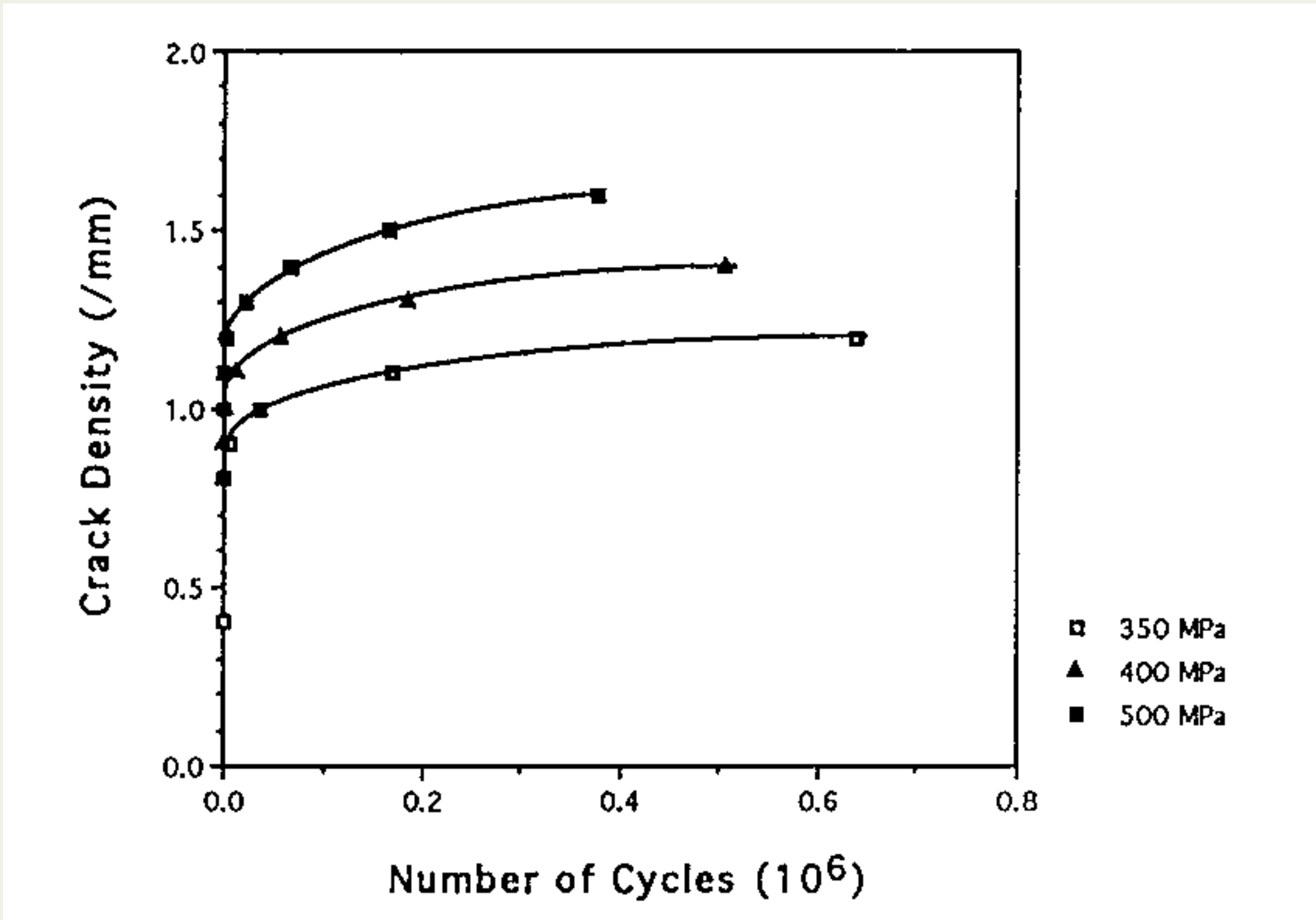
Axial normal stress in 90-plies with and without frictional delamination



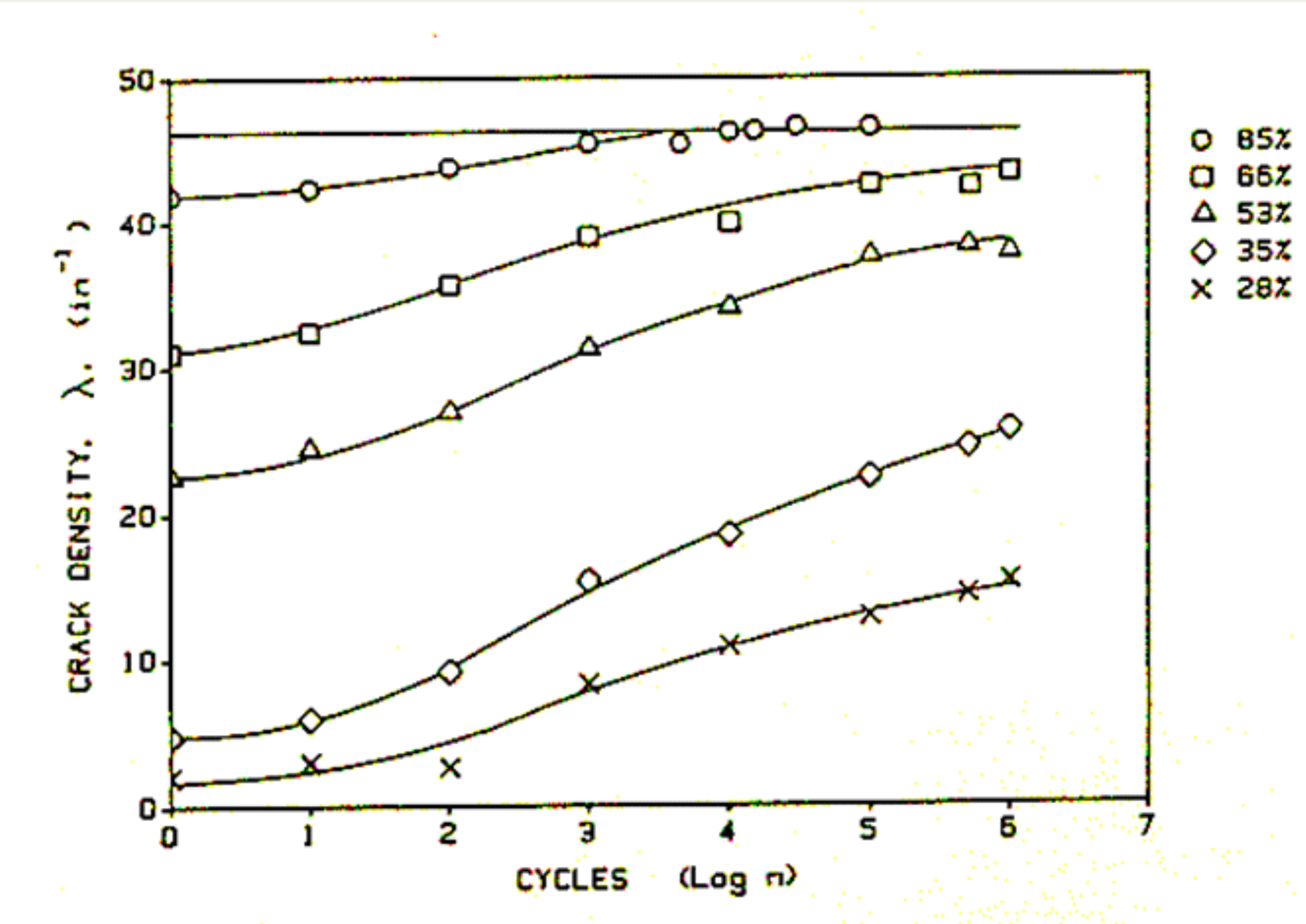


New crack possible

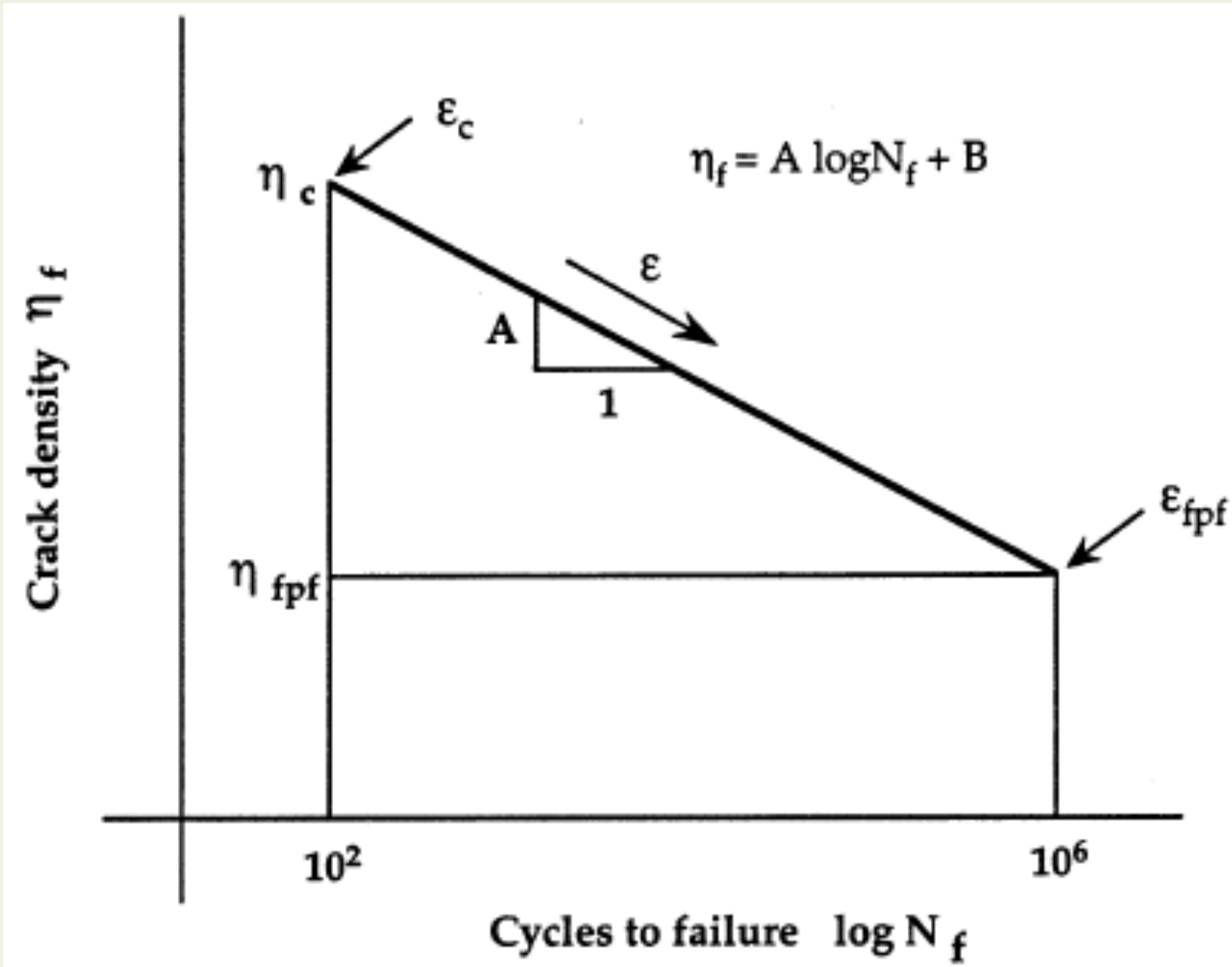
Crack density increase with frictional delamination growth in fatigue



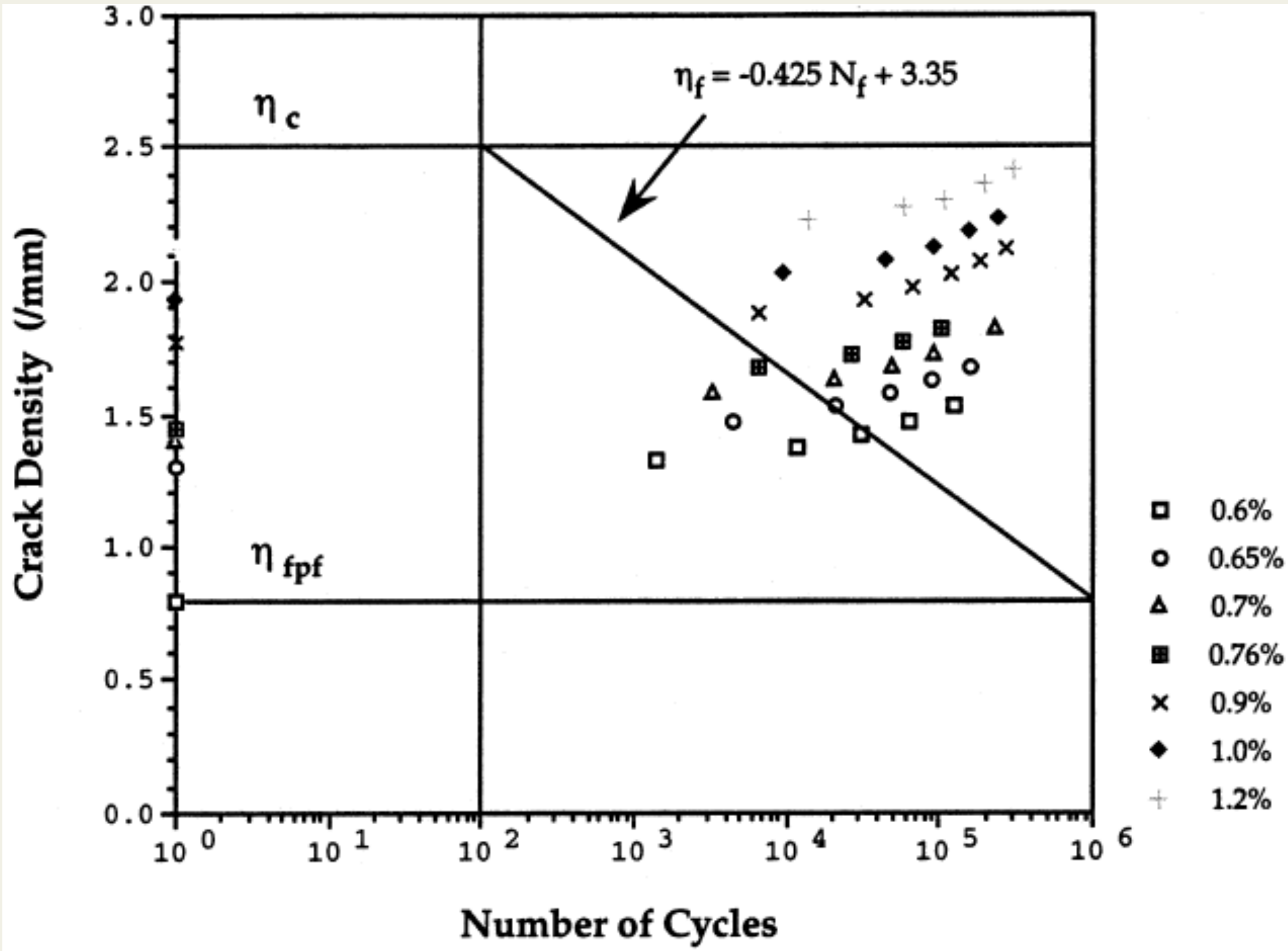
Experimental data showing crack density increase with cyclic loading



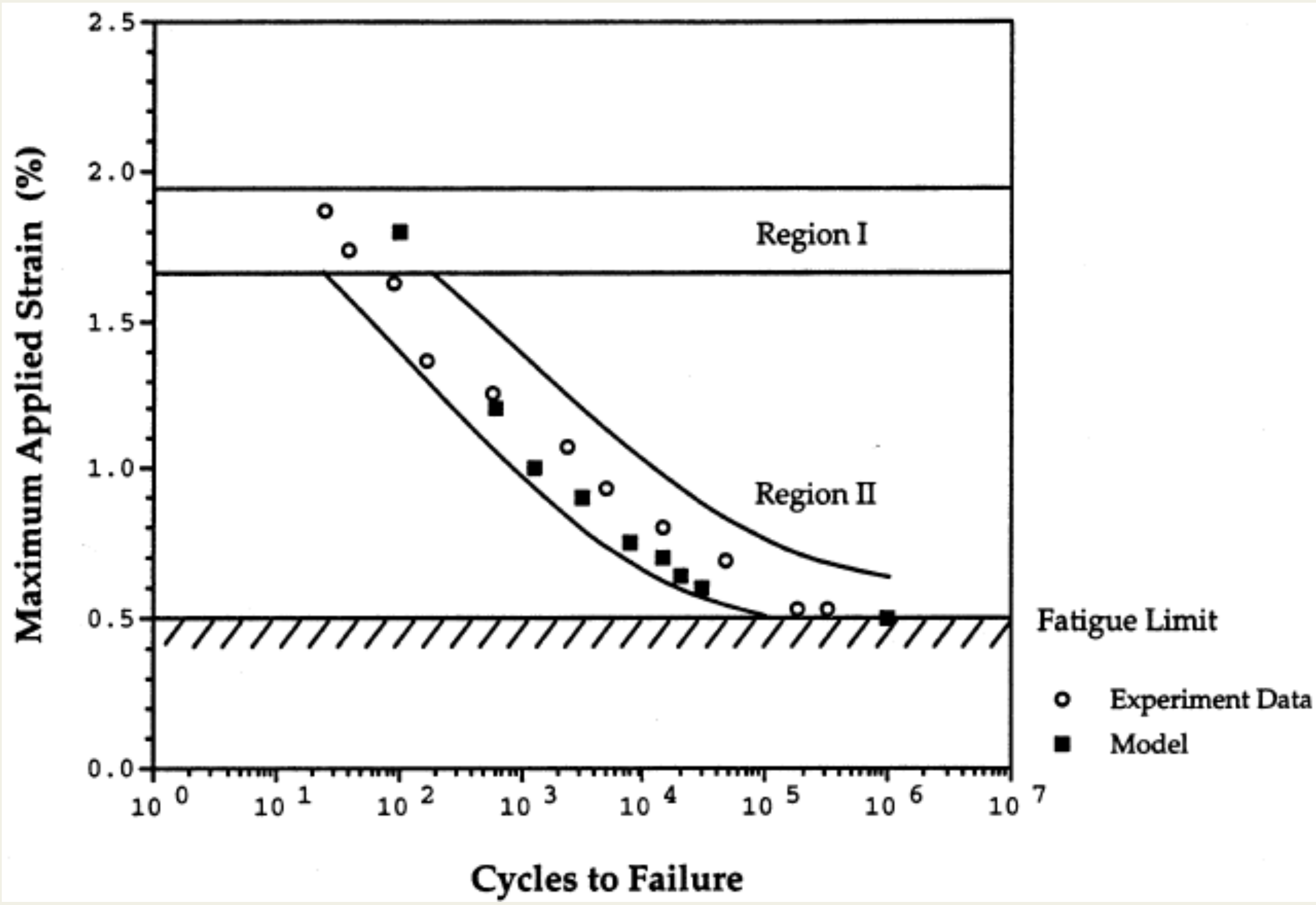
Assumed failure criterion based on crack density variation with cycles



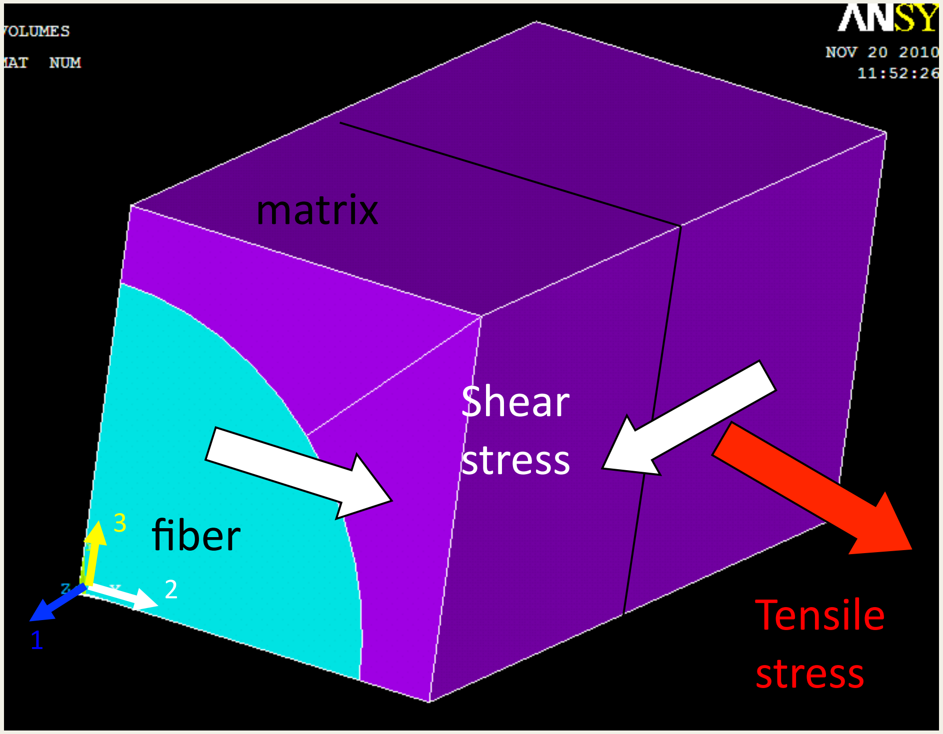
Procedure for fatigue life prediction



Model prediction and test data



Alternative approach to fatigue crack formation based on microstructure



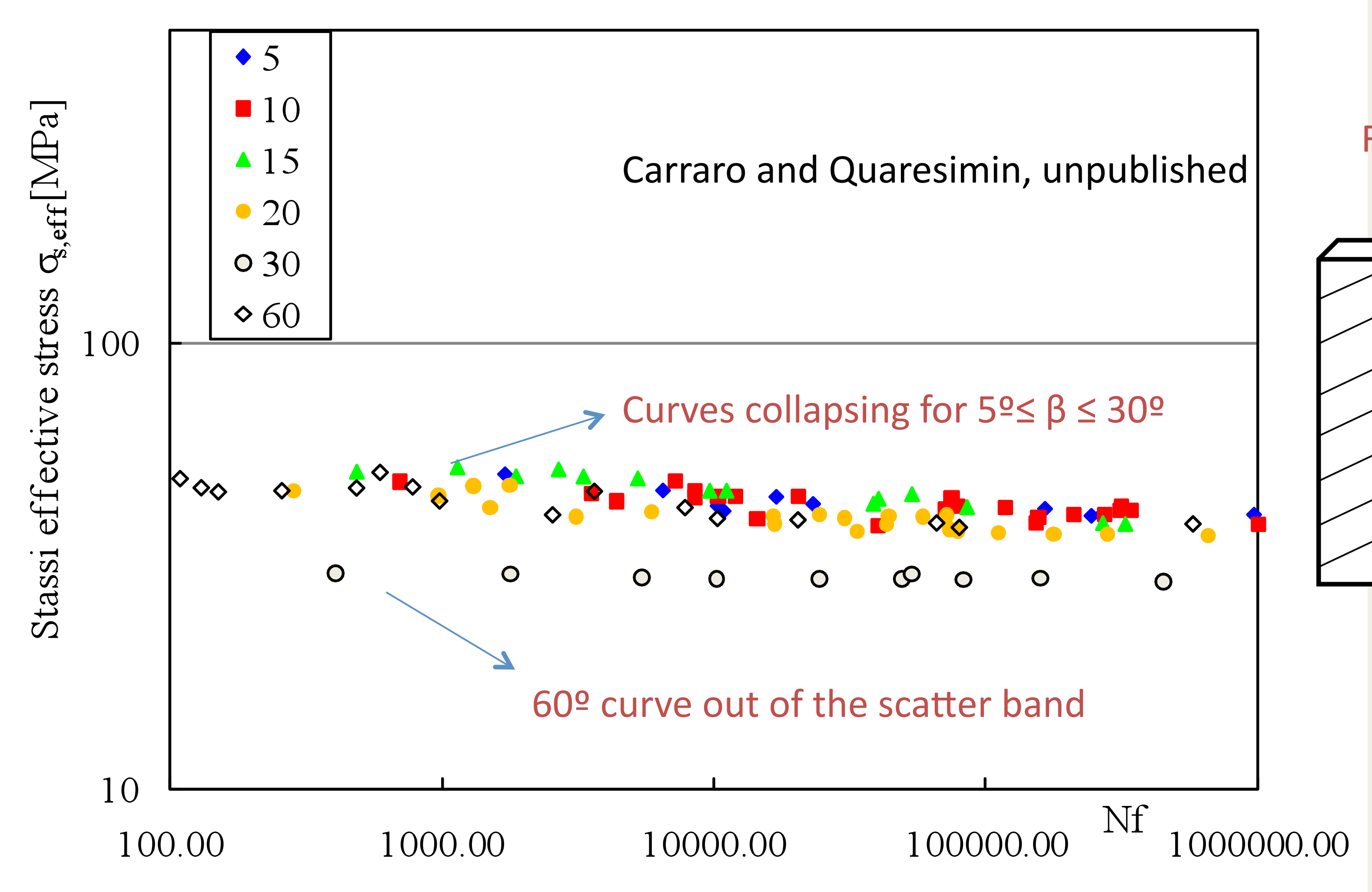
Idea: Investigate the failure process at the fiber/matrix scale under (homogeneous) ply level stresses. Model that failure process in terms of the ply stresses.

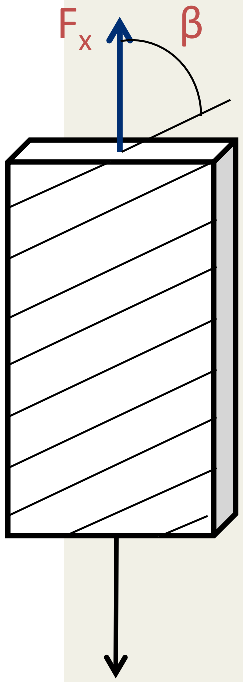
Two competing failure processes:
Dilatational energy controlled vs.
Maximum principal stress controlled
Fiber/matrix debonding

Carraro and Quaresimin (work in progress)

Dilatation vs. Distortion controlled interface failure

Data from Hashin (UD off-axis, R = 0.1)





Concluding Remarks on Fatigue Damage Evolution Modeling

- Phenomenological models are uncertain as they can hit or miss the data since they are not based on observed behavior
- Mechanisms based models are difficult, time consuming to develop, but at the end have the best chance of succeeding
- Multi-scale modeling to develop failure criteria has potential and should be pursued