Fatigue, Damage and Failure of Composite Materials: Mechanisms, Fatigue Life Diagrams and Life Prediction

Ramesh Talreja
Department of Aerospace Engineering
Department of Materials Science and Engineering
Texas A&M University, College Station, Texas, USA

UTMIS Autumn Course, Gothenburg, Sweden, 15-16 October 2019

Lecture 3: FATIGUE LIFE DIAGRAMS - Laminates

Contents

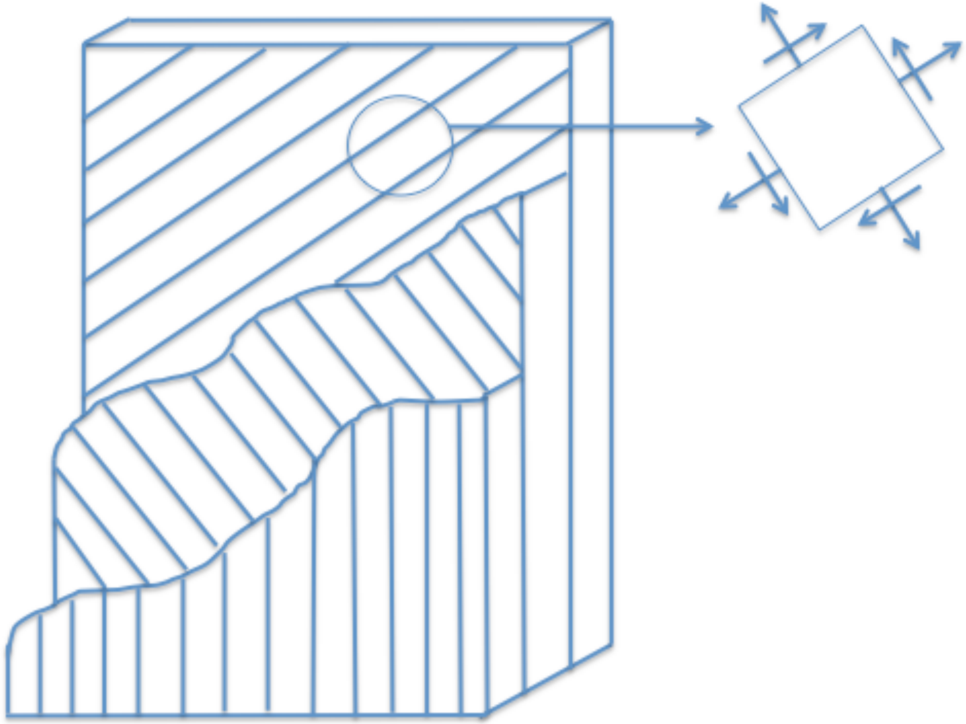
- Damage mechanisms – lamina to laminate
- Lamina (UD composite) fatigue in cyclic plane stress state

$\Rightarrow$ Effect of shear

$\Rightarrow$ Effect of transverse tension

- Changes in the baseline fatigue life diagram of UD composite
- Angle ply laminates
- Cross ply laminates
- General laminates
- Fiber architecture effects: short fiber composites, textile composites

Loading, laminate to lamina



Any general (multiaxial) loading on a laminate results in biaxial loading (plane stress state) in a lamina

In material coordinates, x_1, x_2

the stress components σ_1, σ_2, $\sigma_6 = \sigma_{12}$

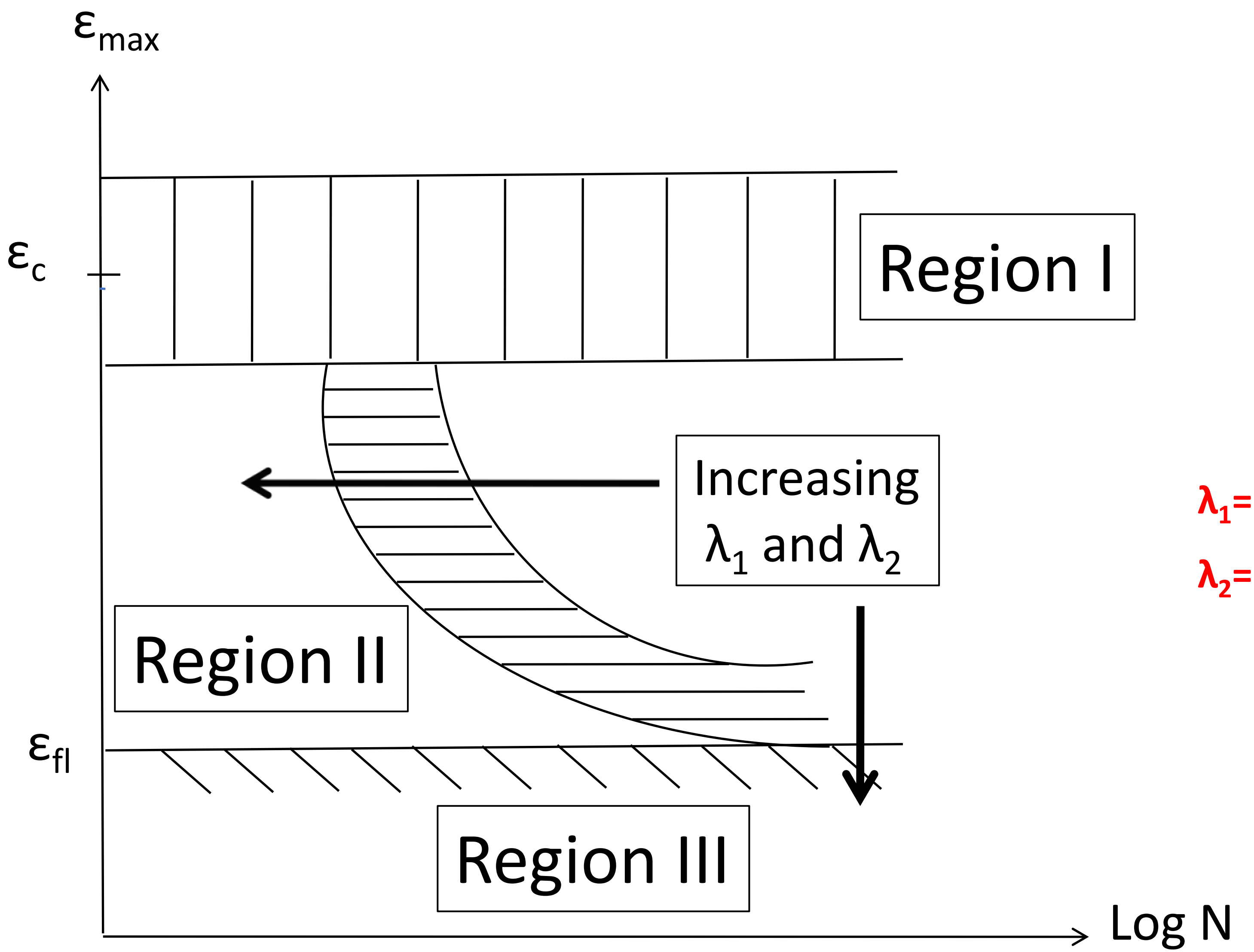
Biaxiality ratios:

$\lambda_1 = \sigma_2 / \sigma_1$ (normal)

$\lambda_2 = \sigma_6 / \sigma_1$ (shear)

How do the biaxiality ratios affect the baseline FLD of UD composites?

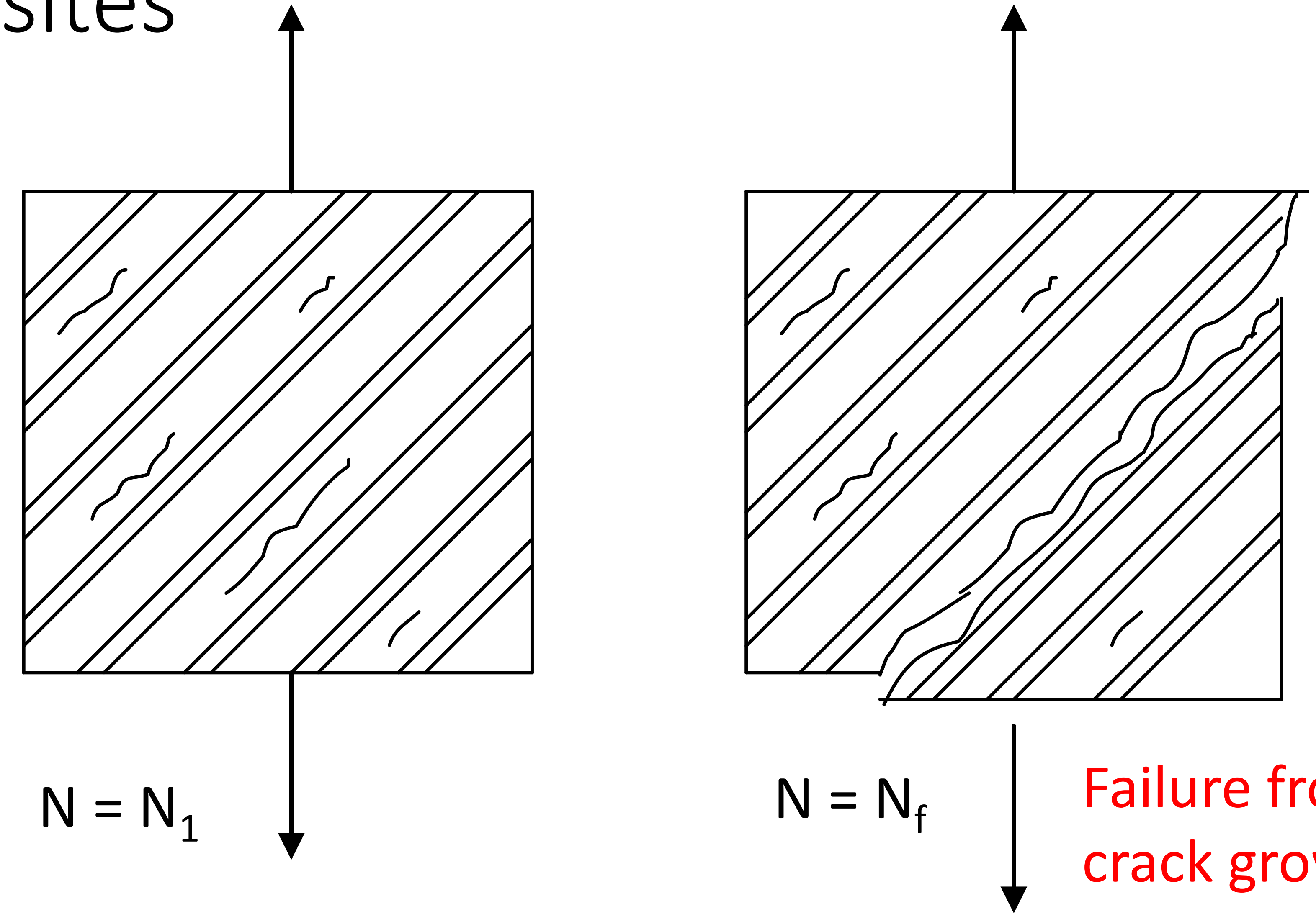
Expected effects of biaxiality ratios on FLD



$\lambda_1 = \sigma_2/\sigma_1$ (normal)

$\lambda_2 = \sigma_6/\sigma_1$ (shear)

Fatigue in off-axis (inclined) tension of UD composites

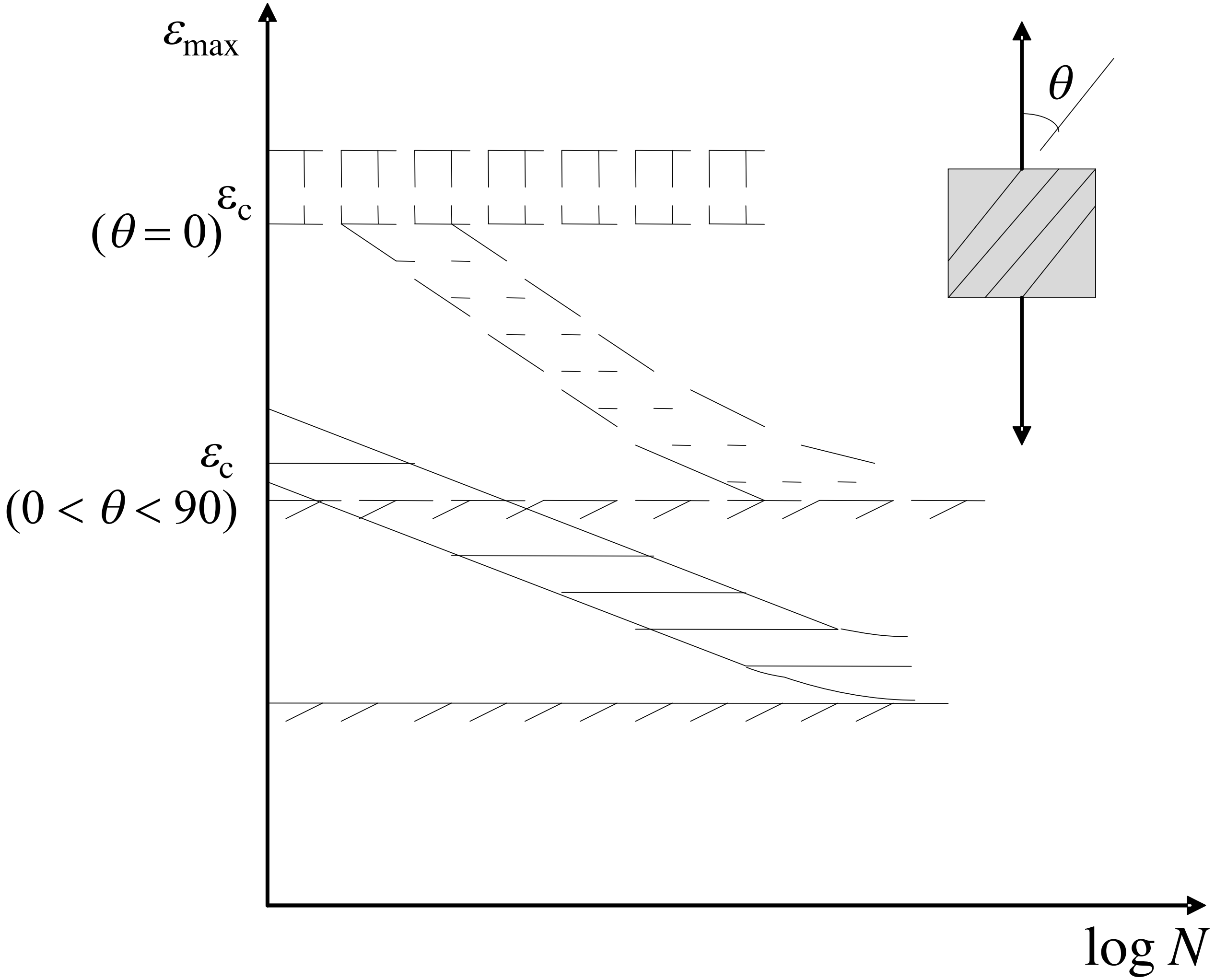


$N = N_1$

$N = N_f$

Failure from a single crack growing in mixed mode

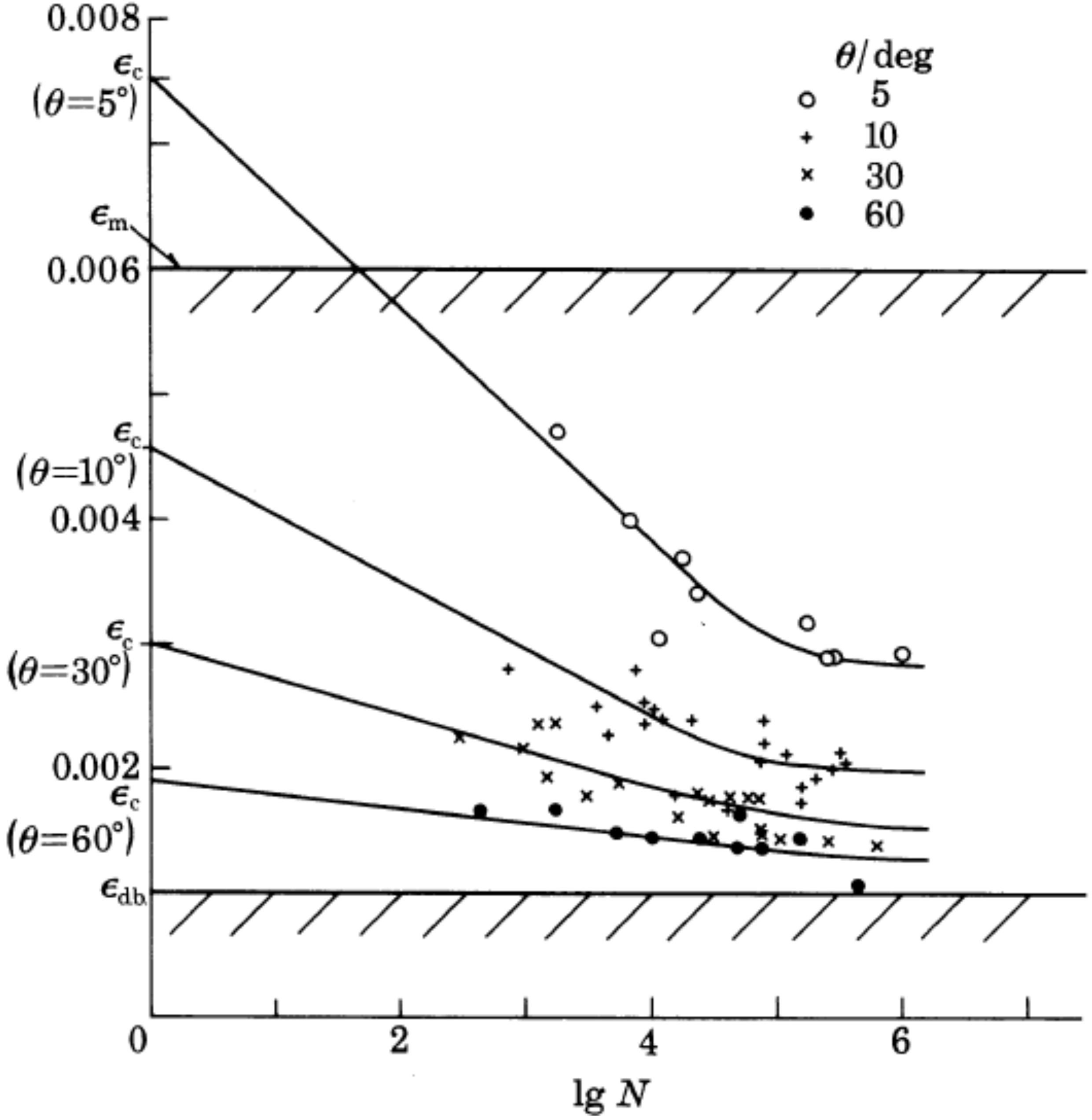
Change in the baseline FLD with the angle of off-axis fatigue loading



Experimental data,
Hashin and Rotem (1973),
Glass/epoxy
(Their S-N data replotted
as FLDs)

ε_m = Fatigue limit of matrix (epoxy)

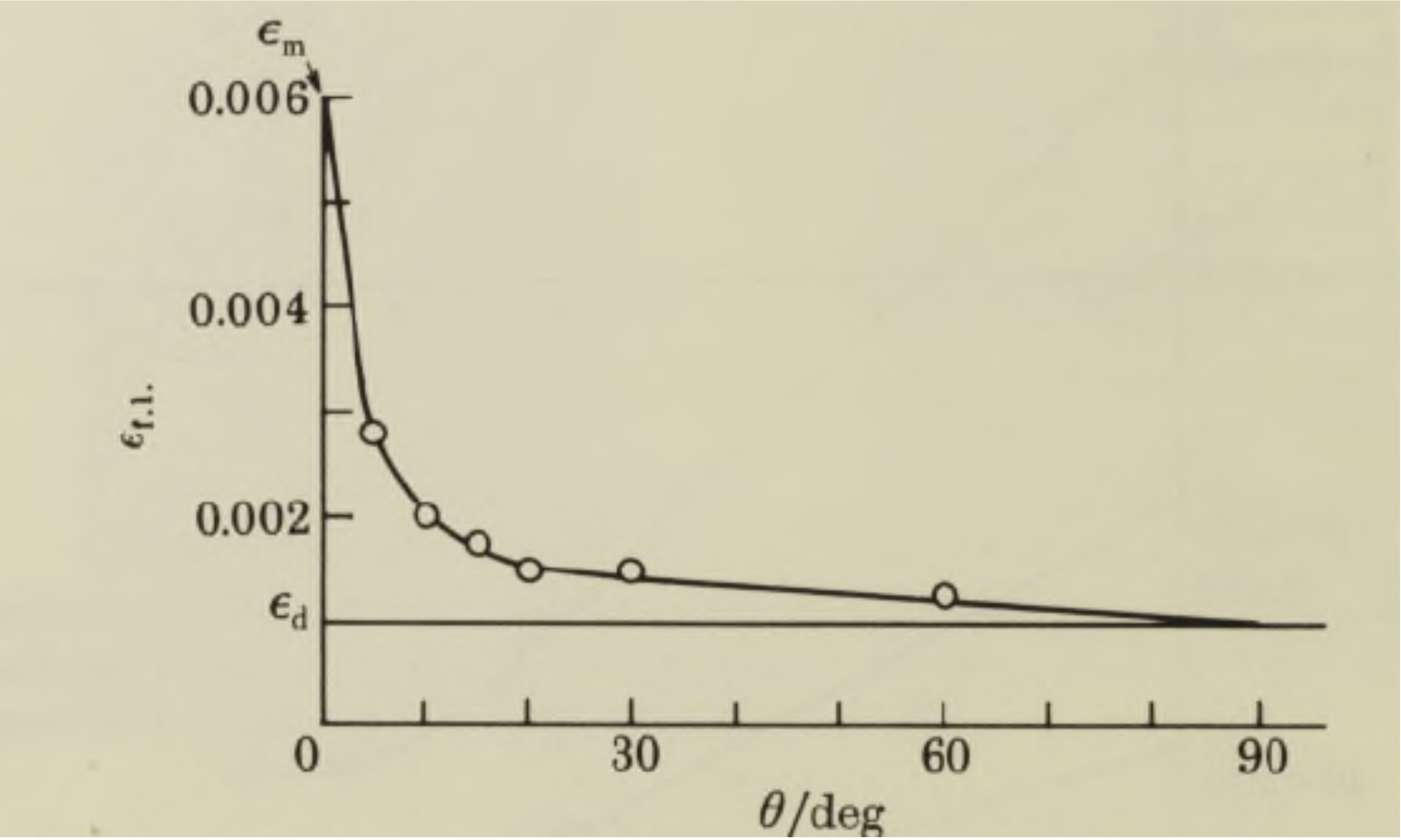
ε_{db} = Strain at initiation of fiber/matrix debonding



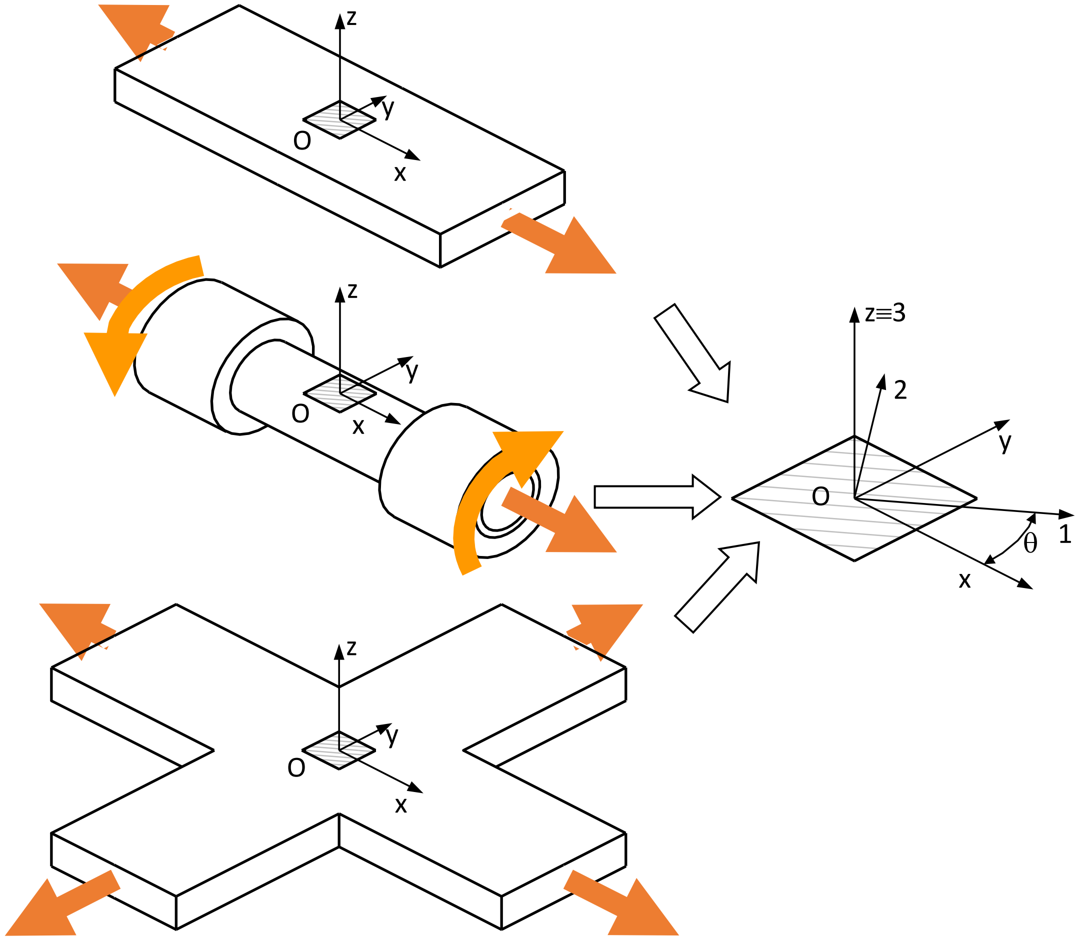
Variation of fatigue limit strain with the off-axis angle

ε_m = Fatigue limit of matrix (epoxy)

ε_d = Strain at initiation of fiber/matrix debonding



Further studies of biaxiality ratio effects using tubular specimens (Courtesy Marino Quaresimin, University of Padova)



Most suited with tubular specimens

Stress biaxiality ratios

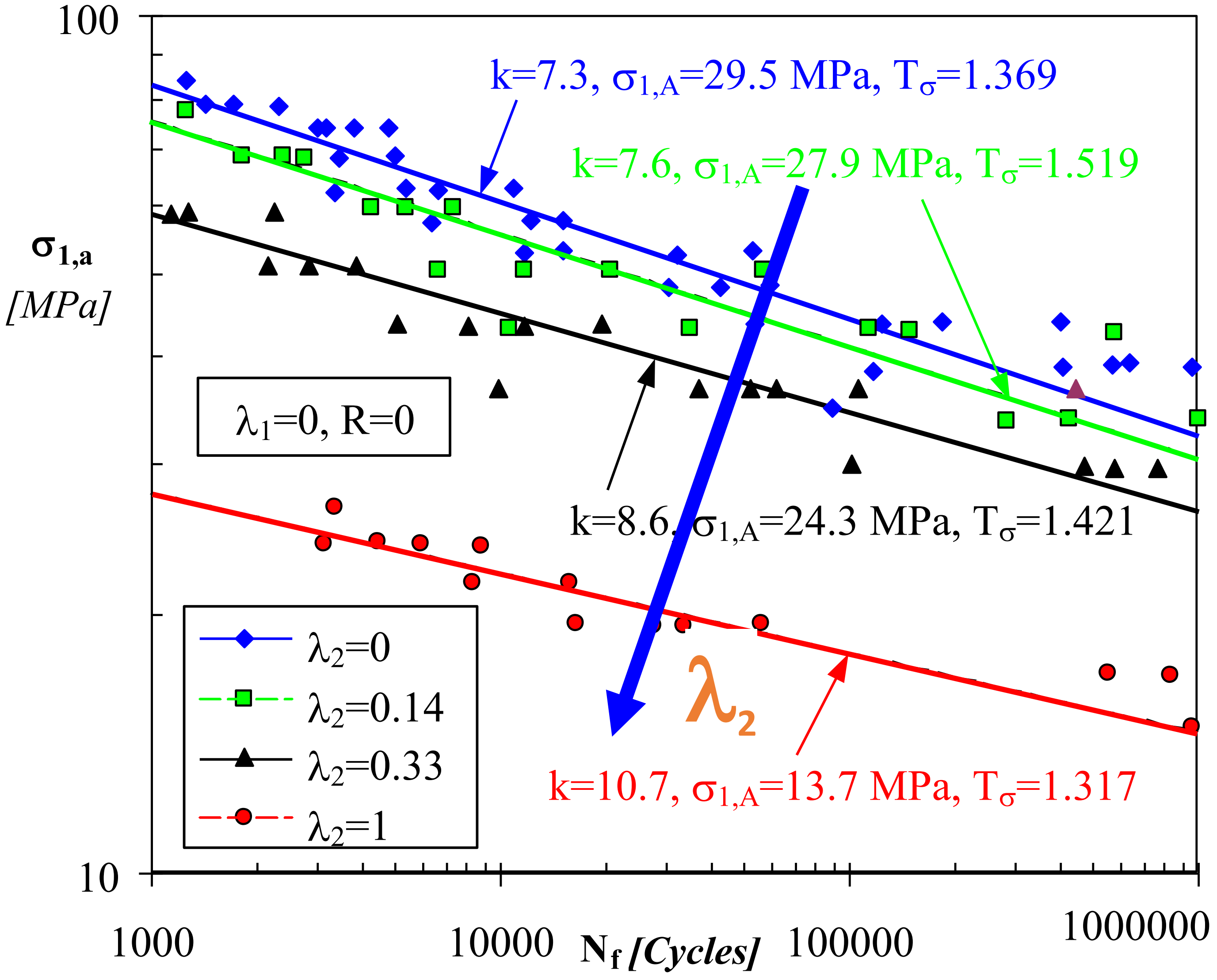
$\lambda_1 = \sigma_2/\sigma_1$ (normal)

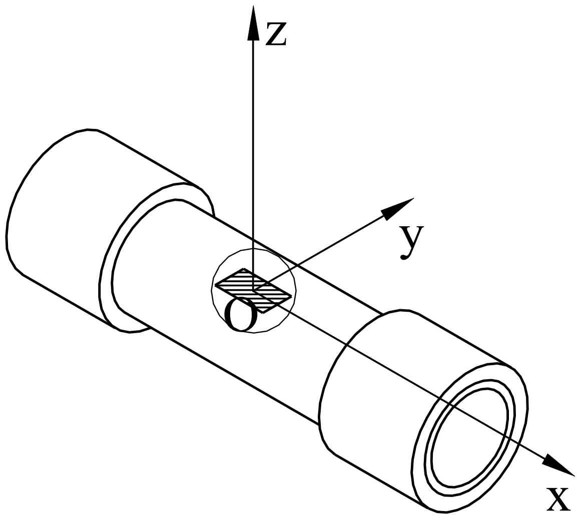
$\lambda_2 = \sigma_6/\sigma_1$ (shear)

$\lambda_{12} = \sigma_6/\sigma_2$ (shear)

$\sigma_6 = \sigma_{12}$

Effect of shear biaxialty ratio λ_2





Glass/Polyester tubular specimen (Tension-Torsion)

$\lambda_2=\sigma_6/\sigma_1$

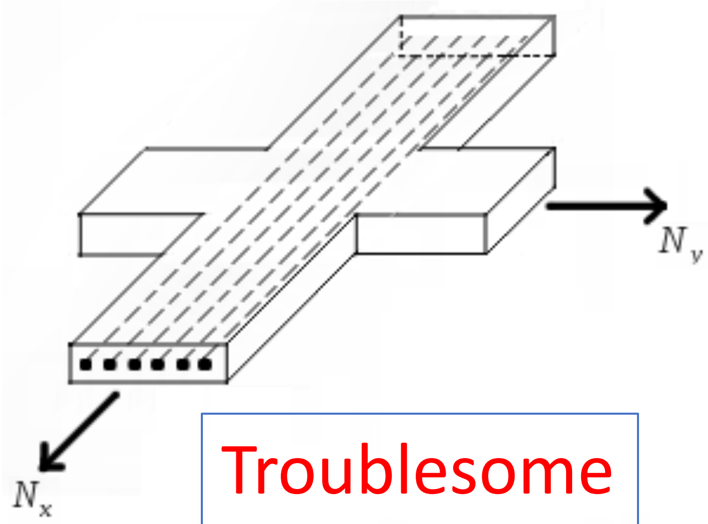
Strong effect of λ_2

Fujii, Shina, Okubo: J. of Composite Materials 28, **3** (1994)

Specimen geometry for multiaxial testing

Cruciform specimen,

$\sigma_6=0$ $\lambda_2=0$ $\lambda_{12}=0$



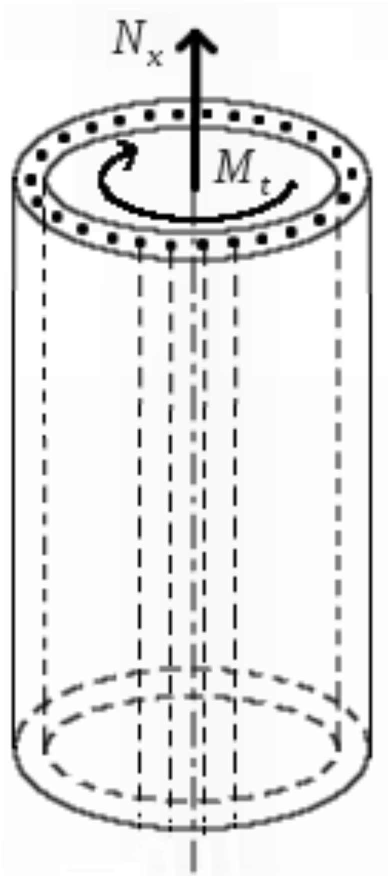
Troublesome Specimen!

$\lambda_1 = \sigma_2/\sigma_1$

$\lambda_2 = \sigma_6/\sigma_1$

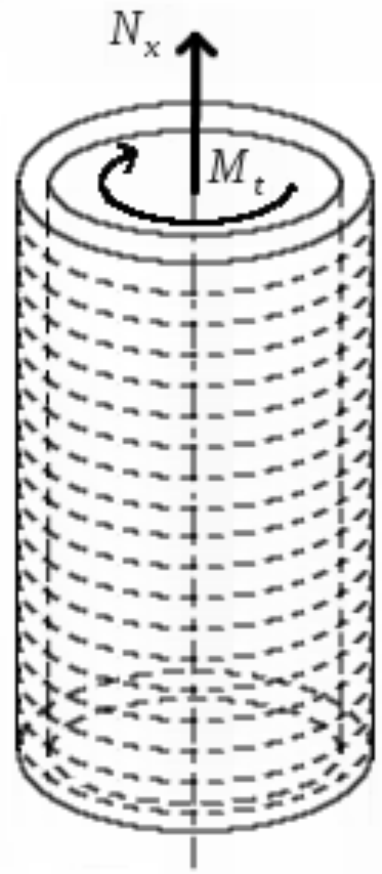
$\lambda_{12} = \sigma_6/\sigma_2$

Tubular specimen, θ= 0º



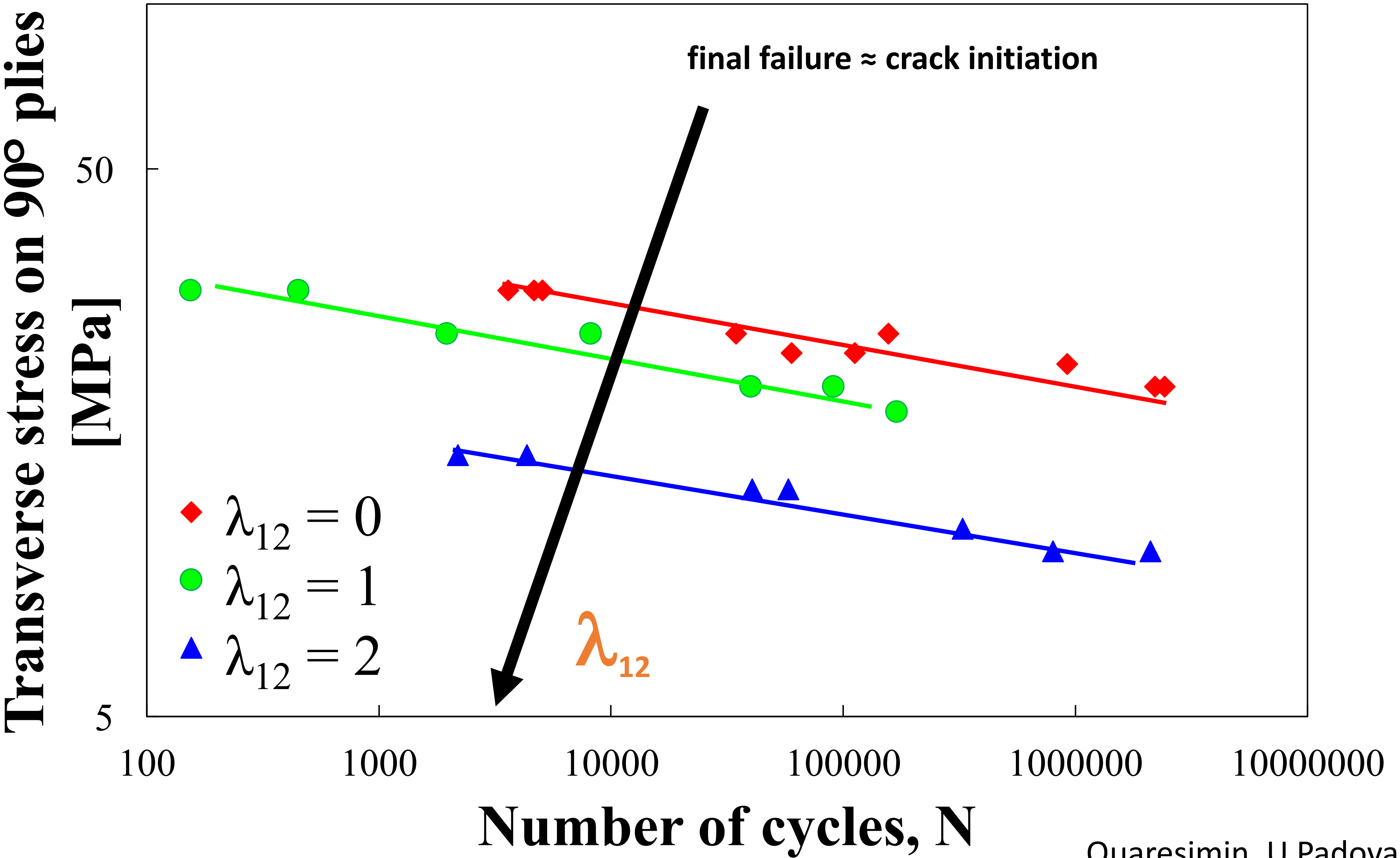
σ_2= 0 λ_1= 0 λ_{12}= ∞
λ_2 = 0 pure tension
λ_2 = ∞ pure torsion
λ_2 ≠0 tens+tors

Tubular specimen, θ= 90º



σ_1= 0 λ_1= ∞ λ_2= ∞
λ_{12} = 0 pure tension
λ_{12} = ∞ pure torsion
λ_{12} ≠0 tens+tors

Fatigue curves (σ_6 on σ_2) at R=0 $[90]_4$ tubes

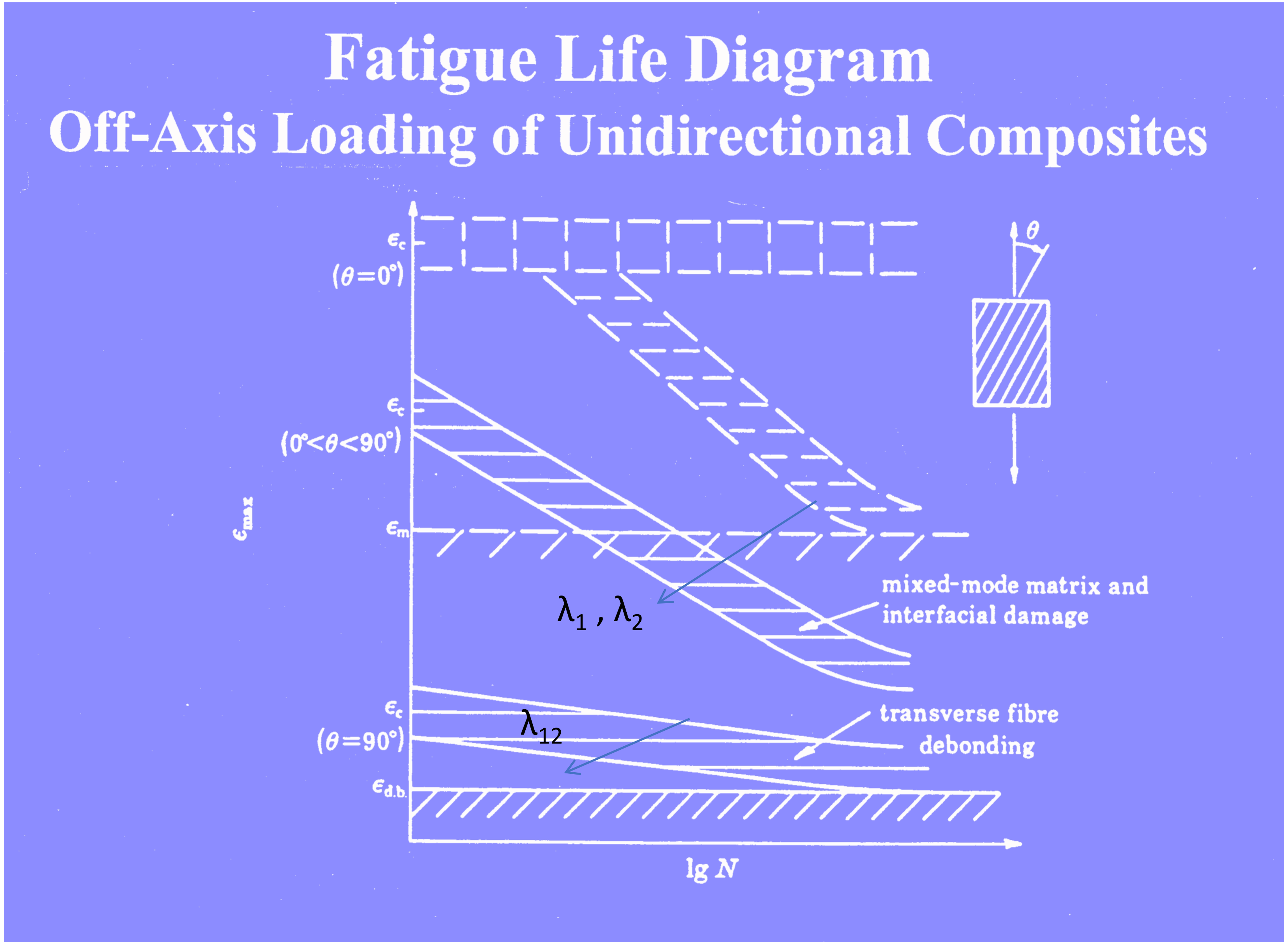


Quaresimin, U Padova

Transverse cracks observed
In 90^0 tubes under tension σ_2
and torsion σ_{12}

Quaresimin, U Padova

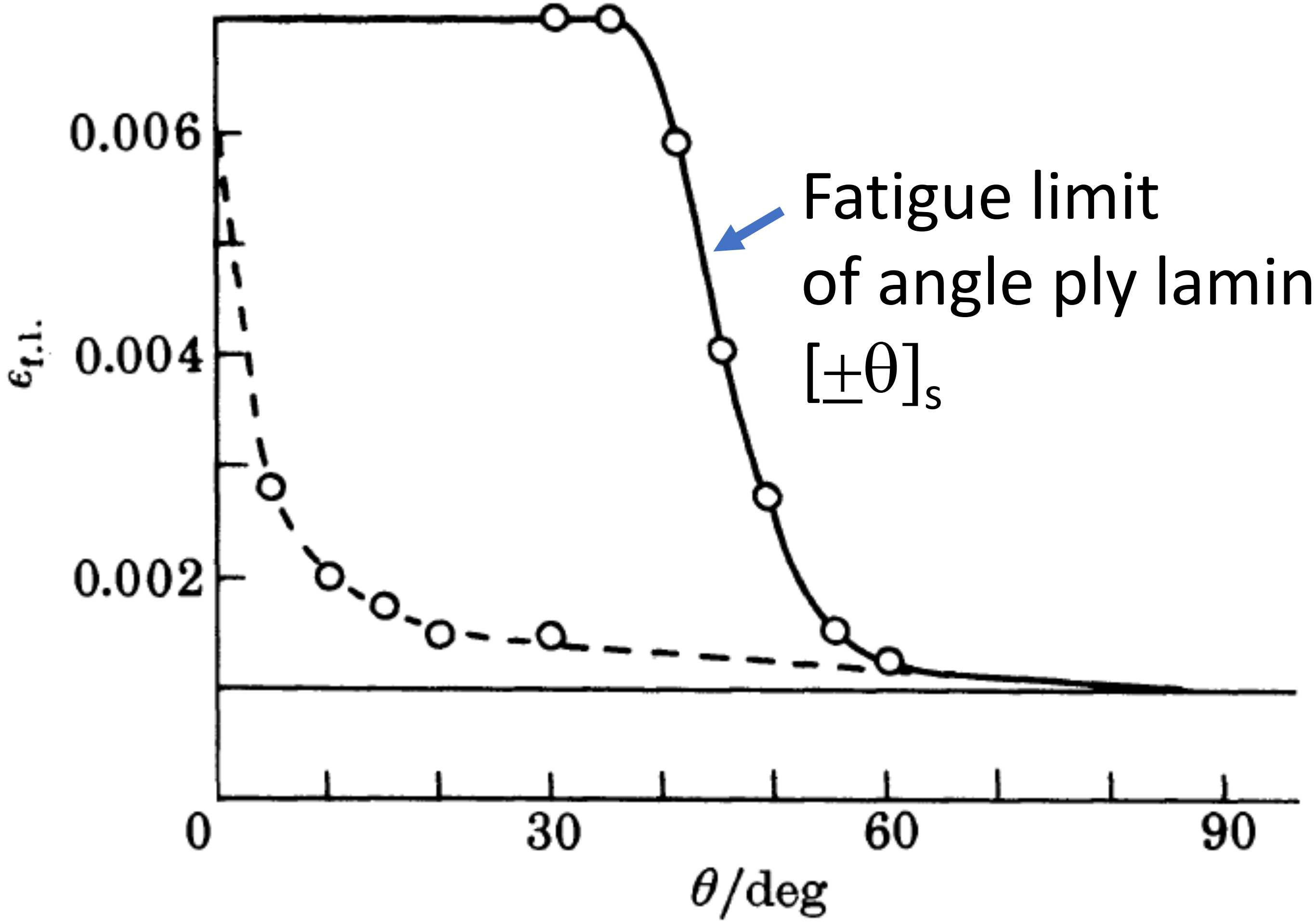
Baseline fatigue life diagram modified by $\lambda_{1,}\ \lambda_2$ and λ_{12}



Fatigue Life Diagram

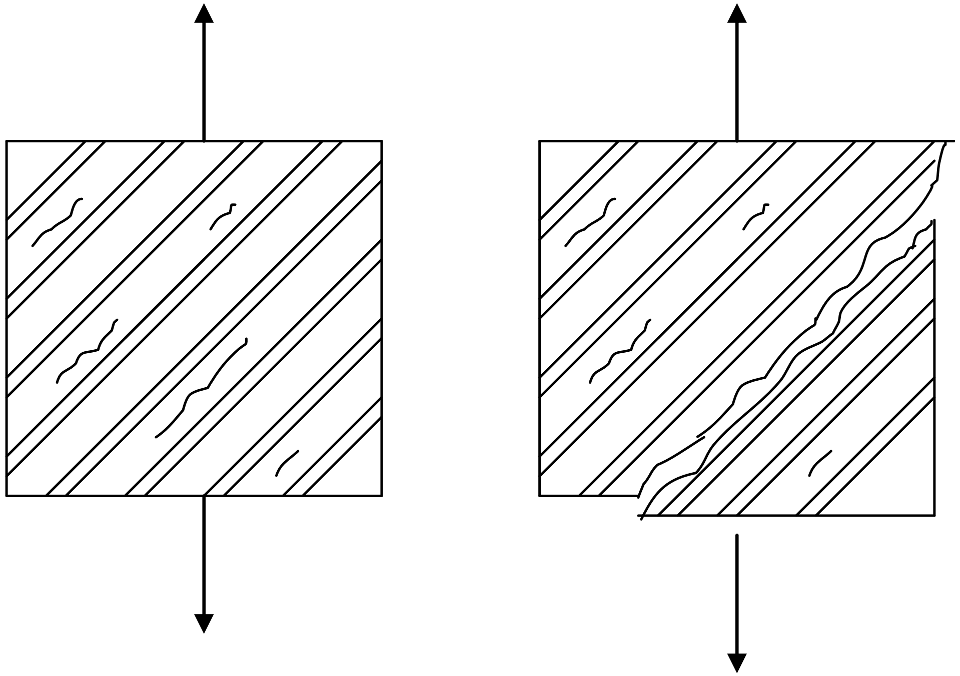
Off-Axis Loading of Unidirectional Composites

Fatigue limit strain in UD and angle ply laminate with off-axis angle

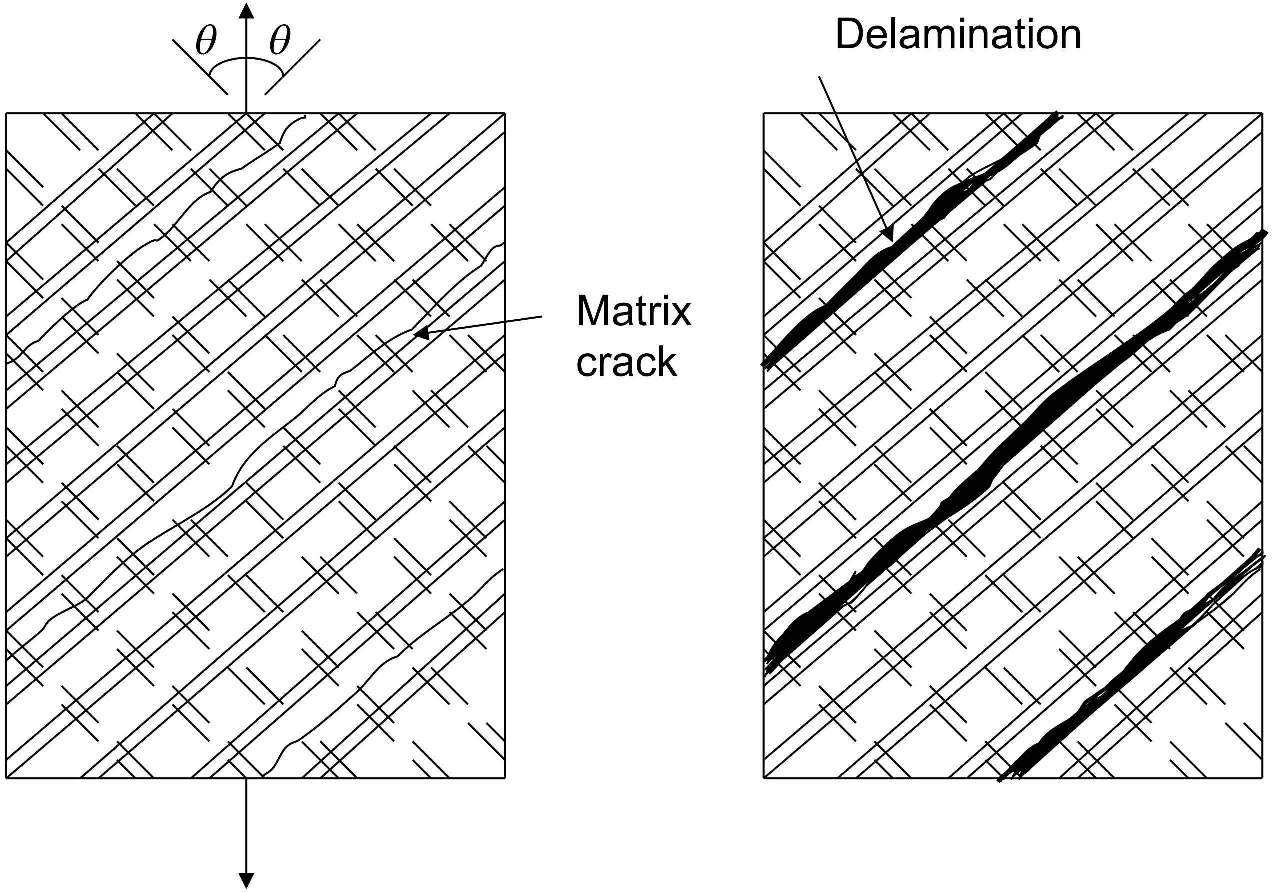


Fatigue limit
of angle ply laminate
$[\pm\theta]_s$

Off-axis loading of UD vs. Angle ply laminates: Damage mechanisms

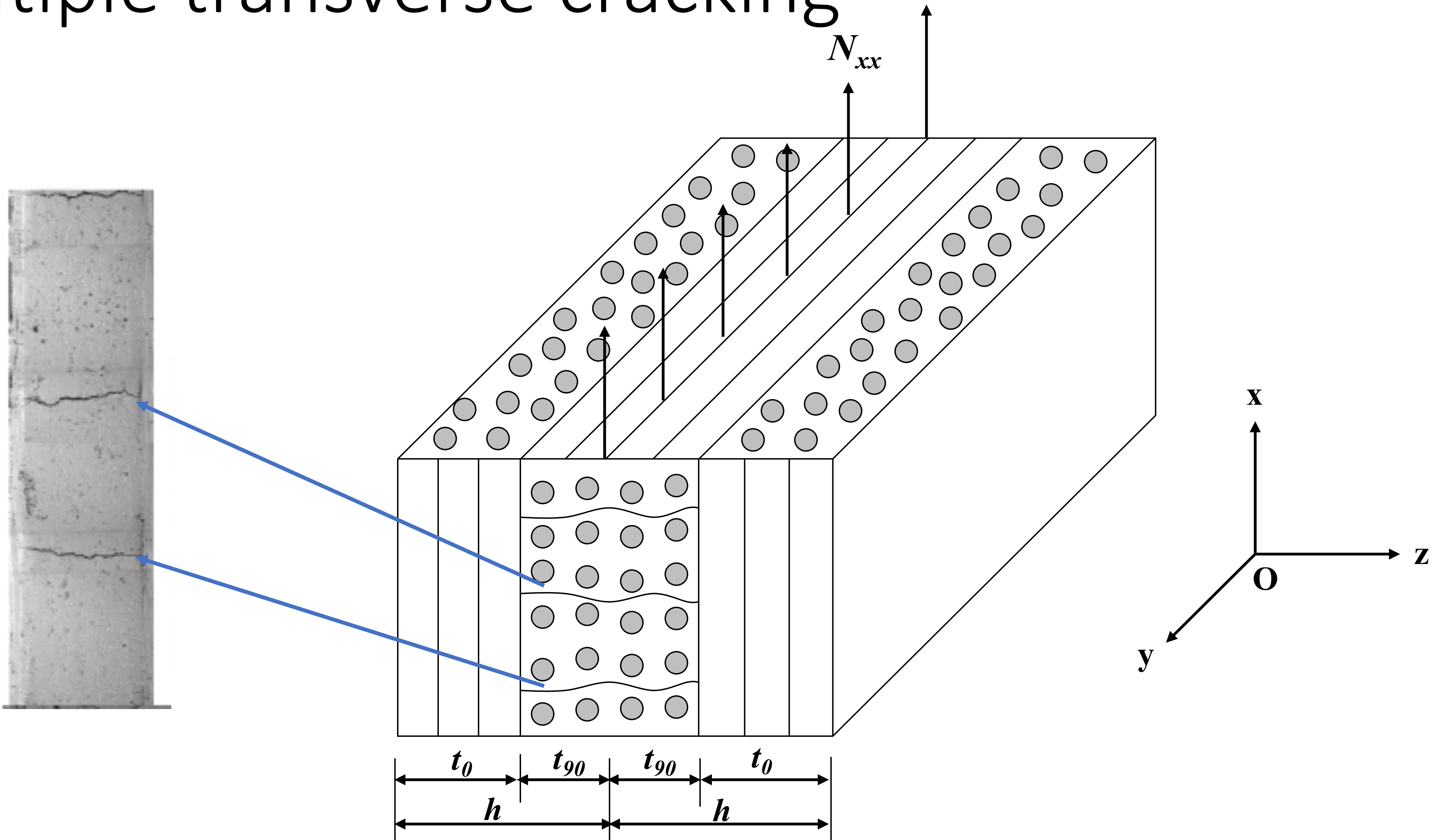


UD Composite

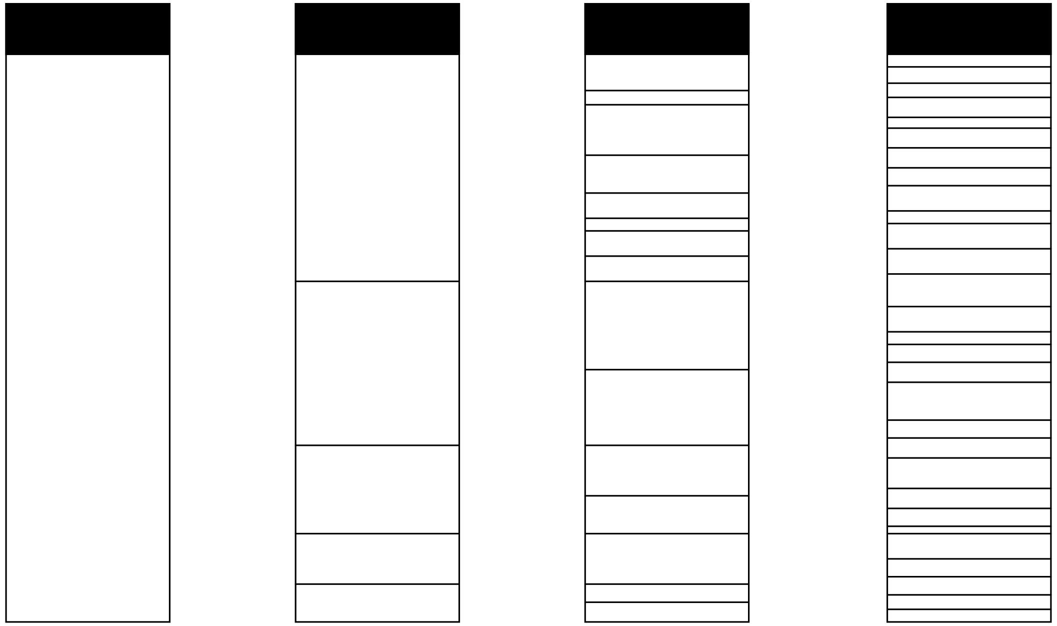


Angle Ply Laminate

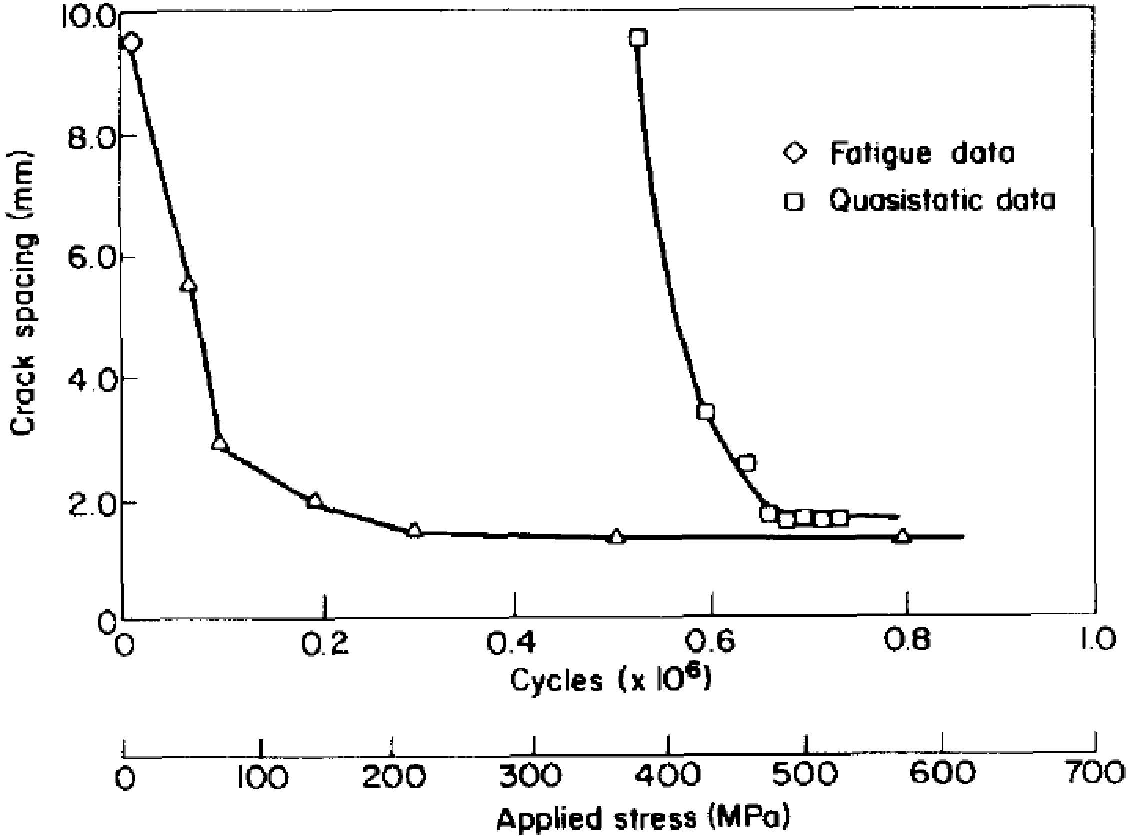
Cross Ply Laminates - Damage mechanism: Multiple transverse cracking



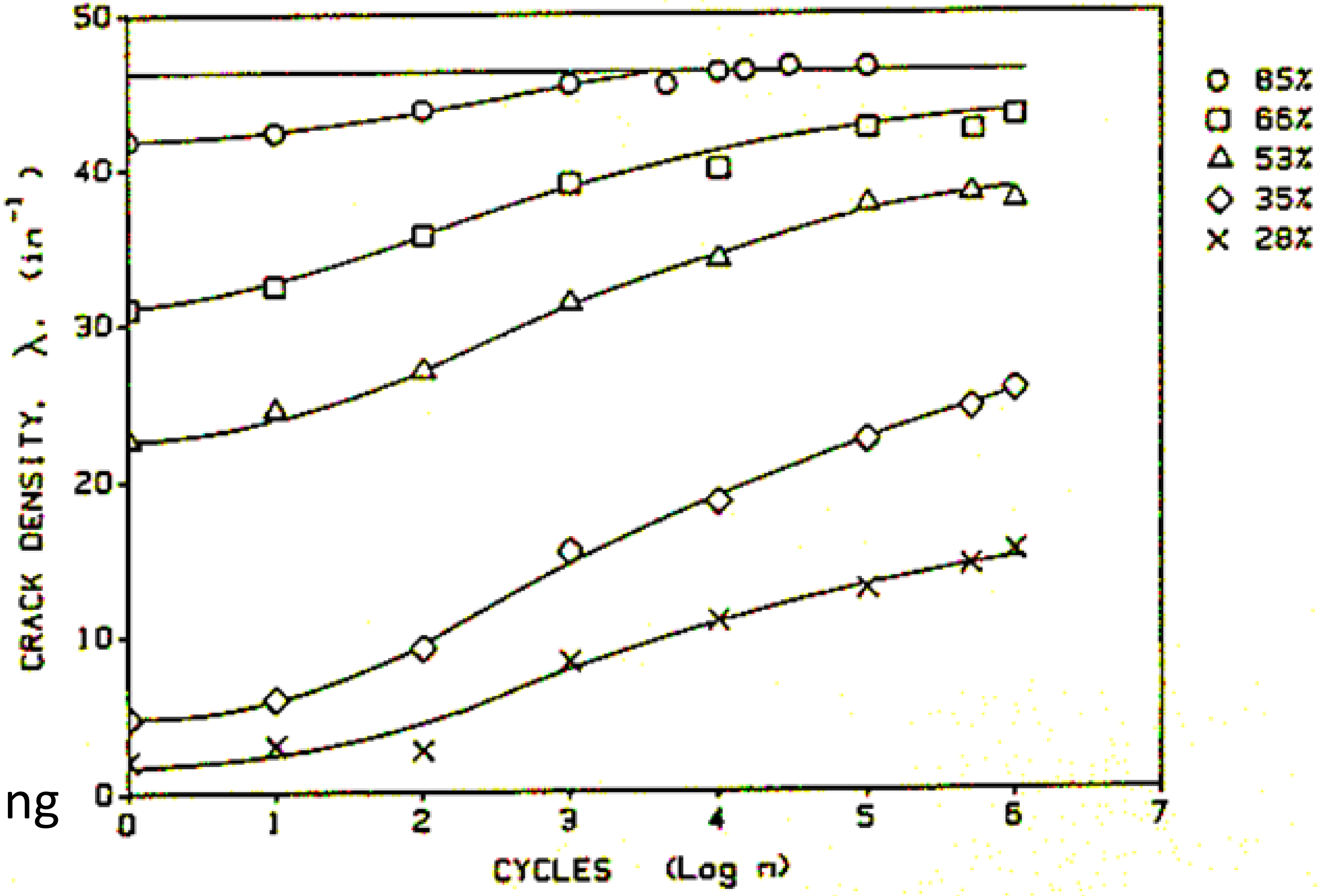
Progression of multiple transverse cracking



Transverse cracks with increasing stress or number of cycles



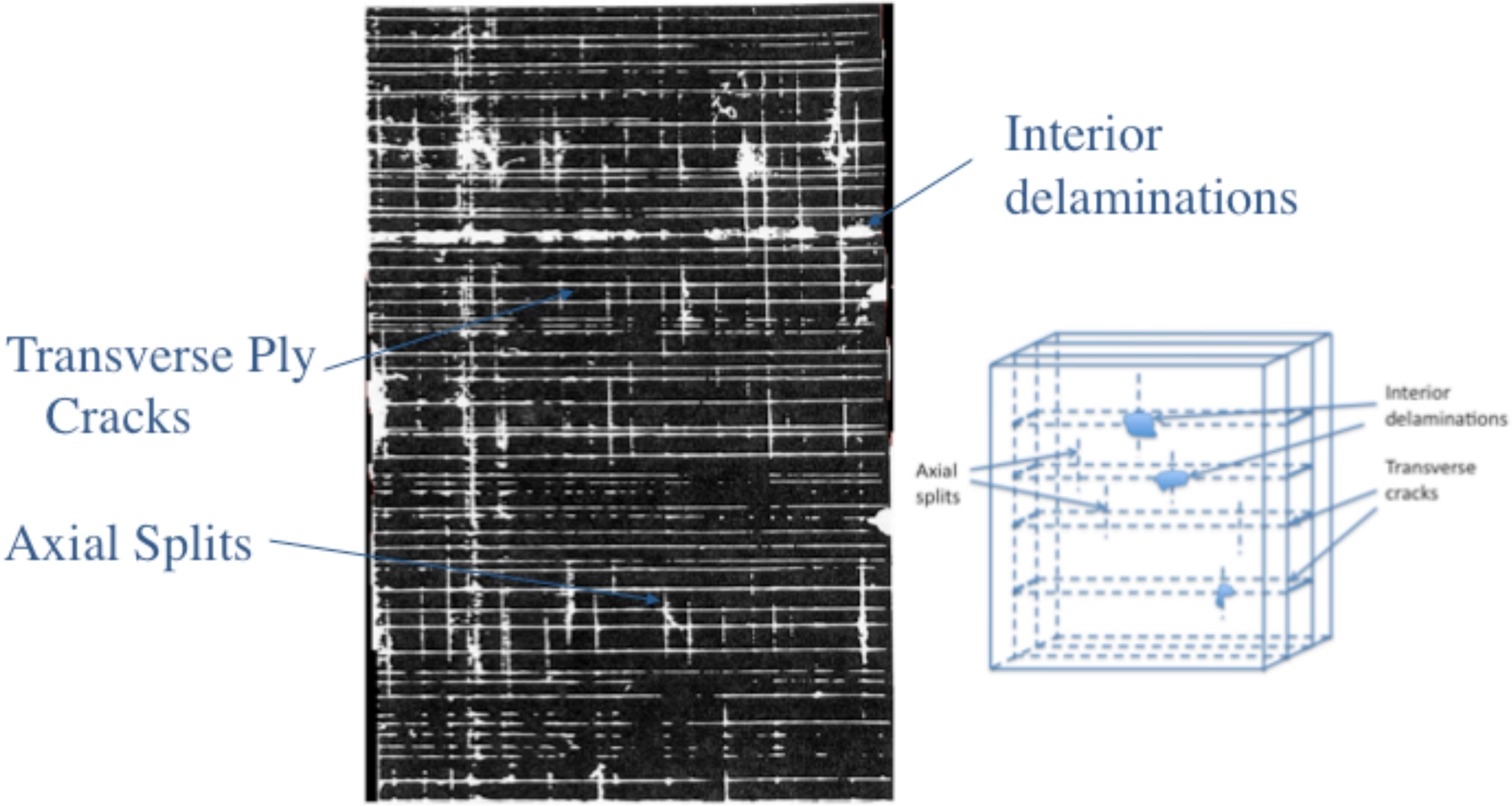
Progression of transverse cracking with max fatigue load level

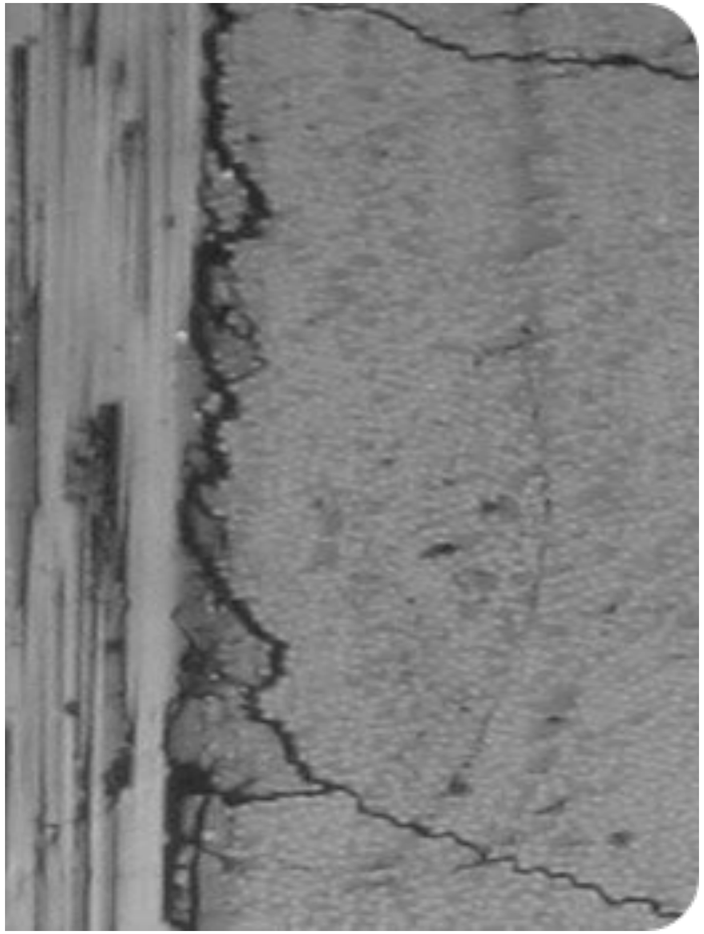


% of failure load

Crack density = Inverse of crack spacing

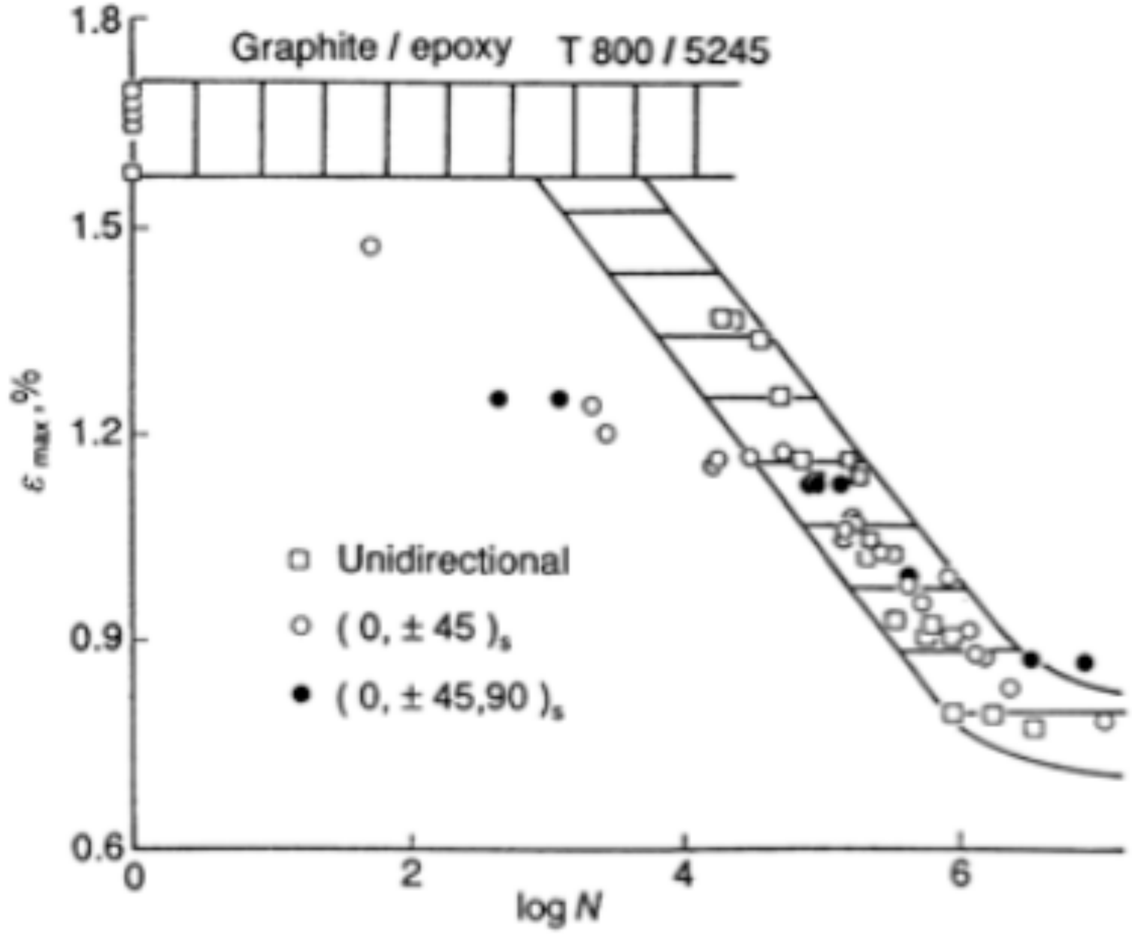
All damage mechanisms under fatigue of cross ply laminates





Delamination caused by transverse crack deflection (Varna, LTU, Sweden)

FLD of laminates related to the baseline FLD of UD composites



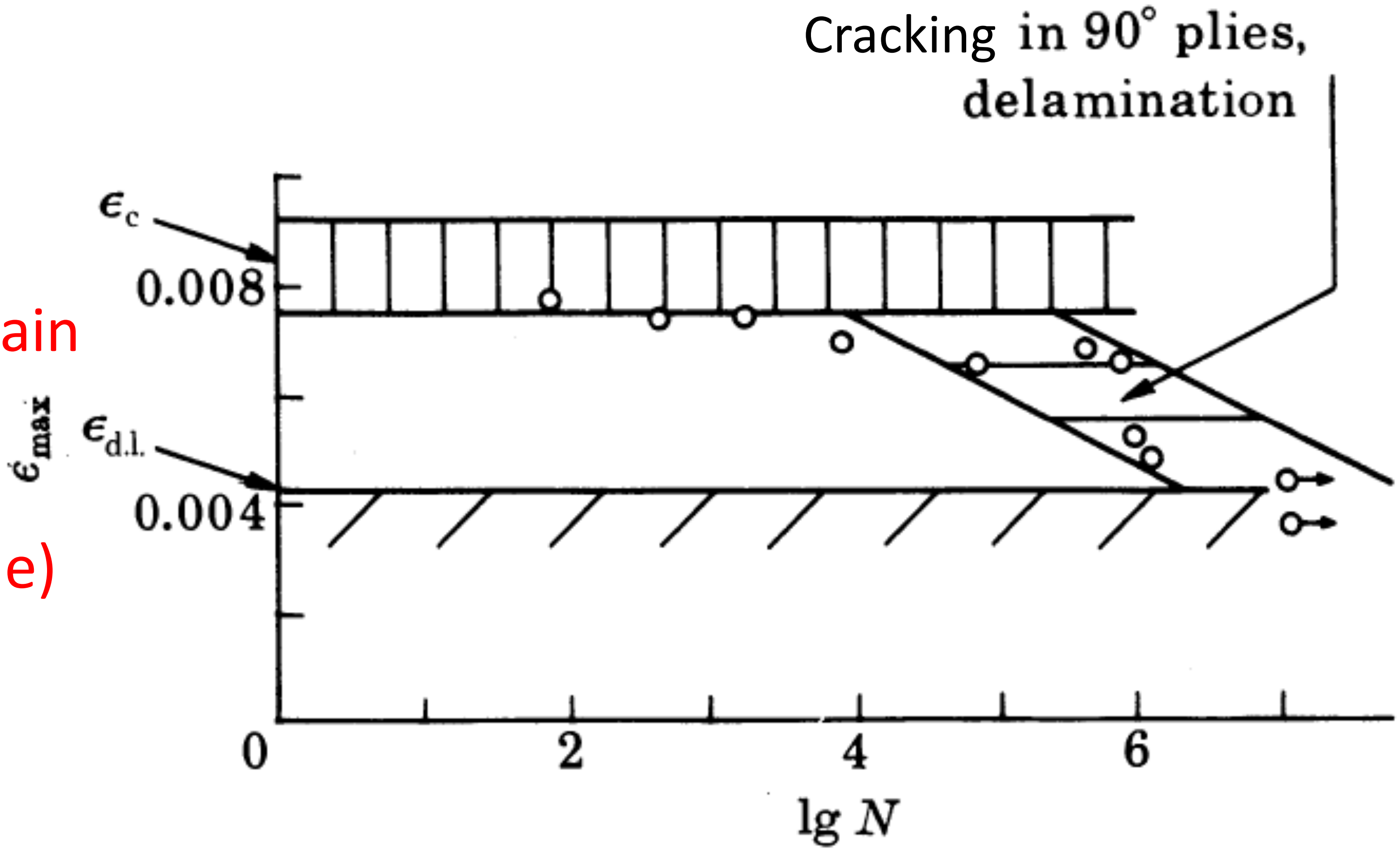
Observations:

- Region II of FLD of laminates deviates to left (earlier failure) caused by additional damage mechanisms.
- Region I exists in laminate FLDs if 0-degree plies are present.

FLD of a cross ply laminate

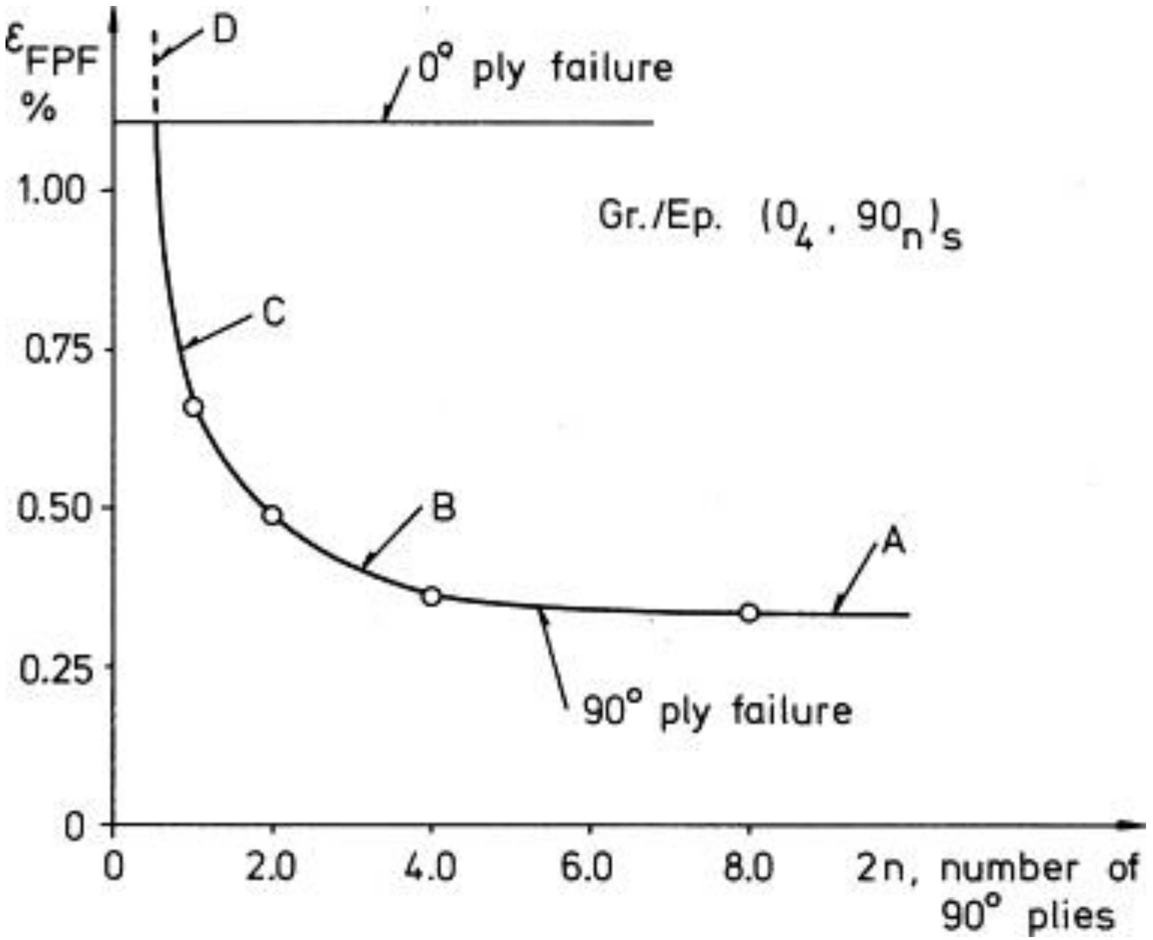
Note:

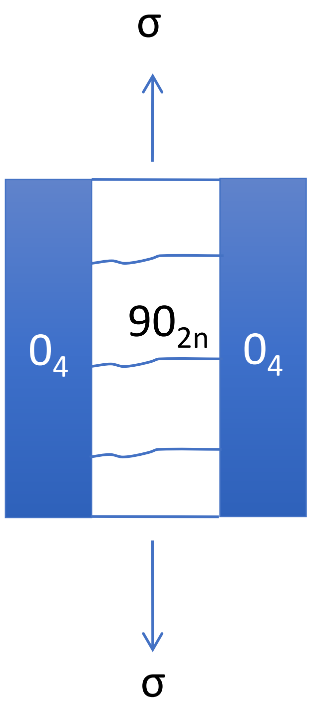
1. Region I decided by the fiber failure strain
2. Fatigue limit given by the first dissipative (irreversible) mechanism



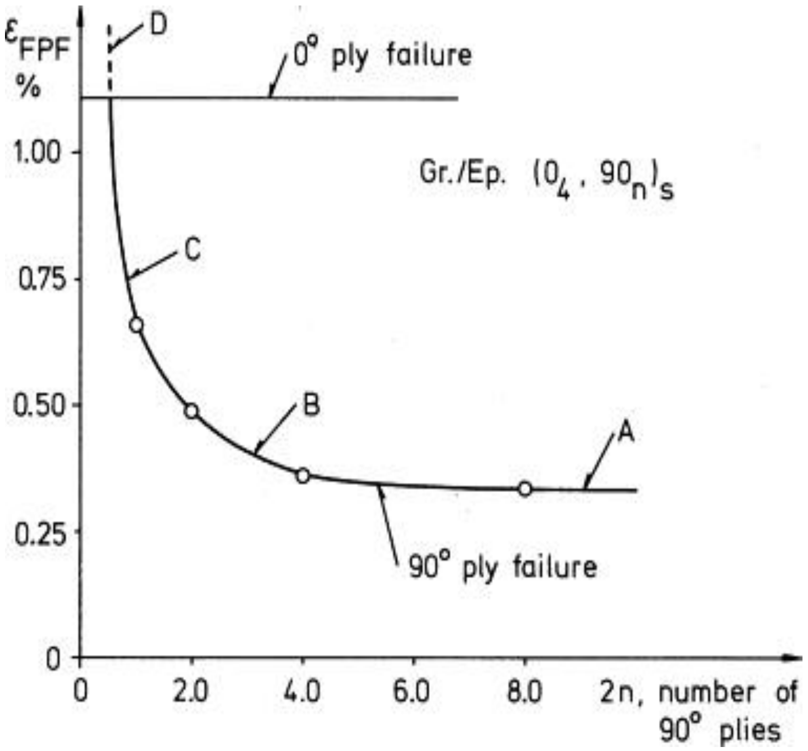
Data from Grimes, 1977

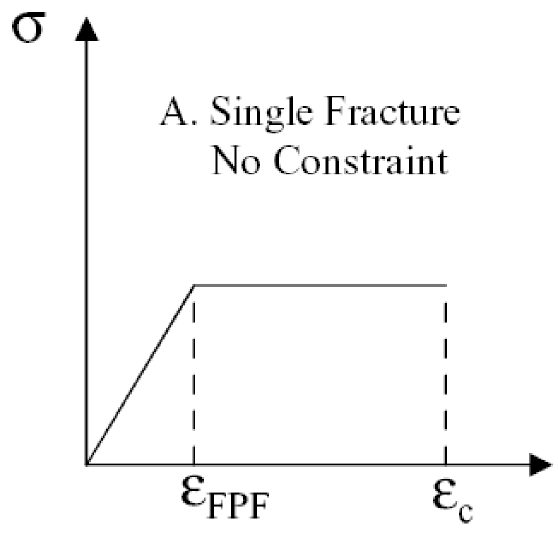
Fatigue limit of cross ply laminates: Strain to initiation of transverse cracking

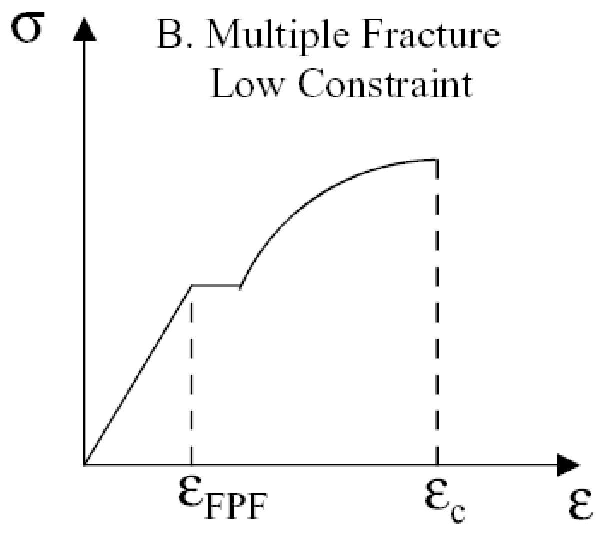


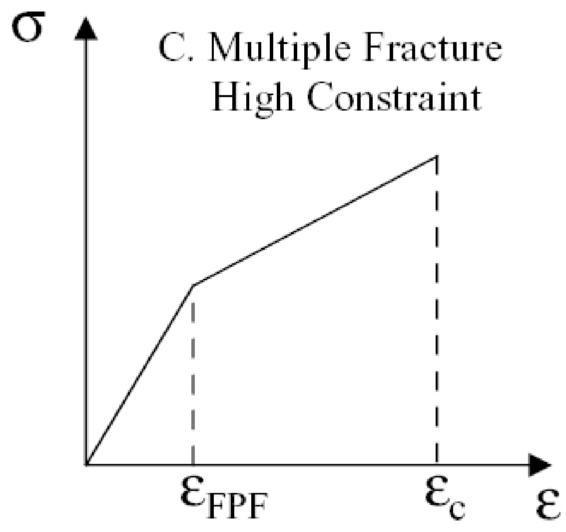


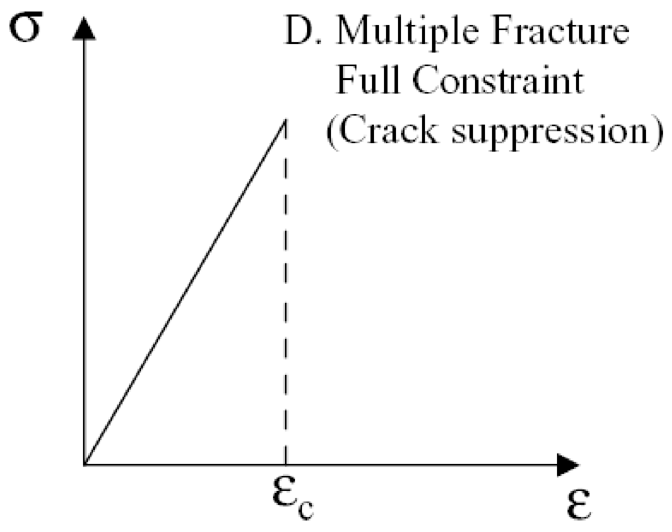
ε_{FPF}: laminate strain at which multiple cracking initiates







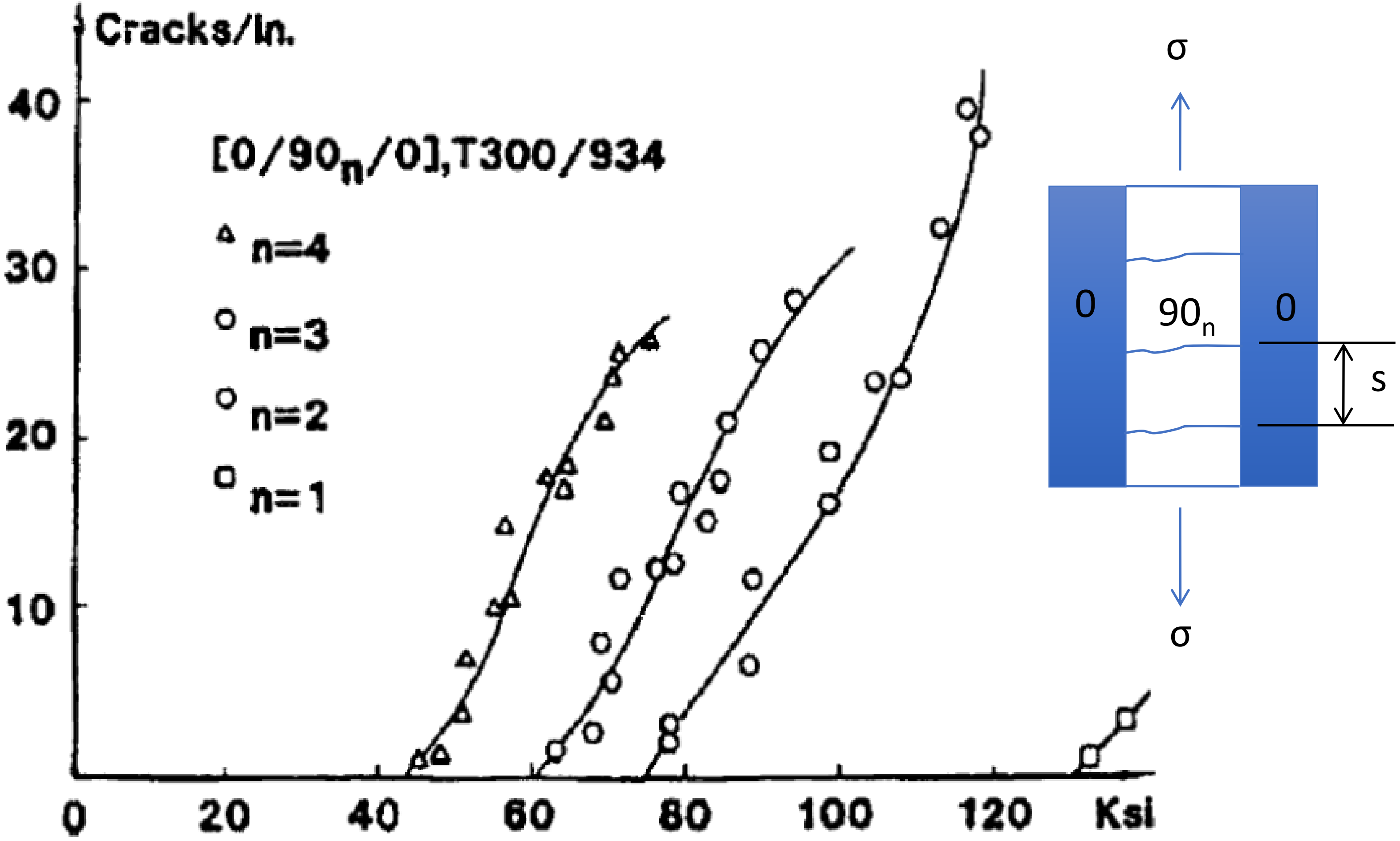




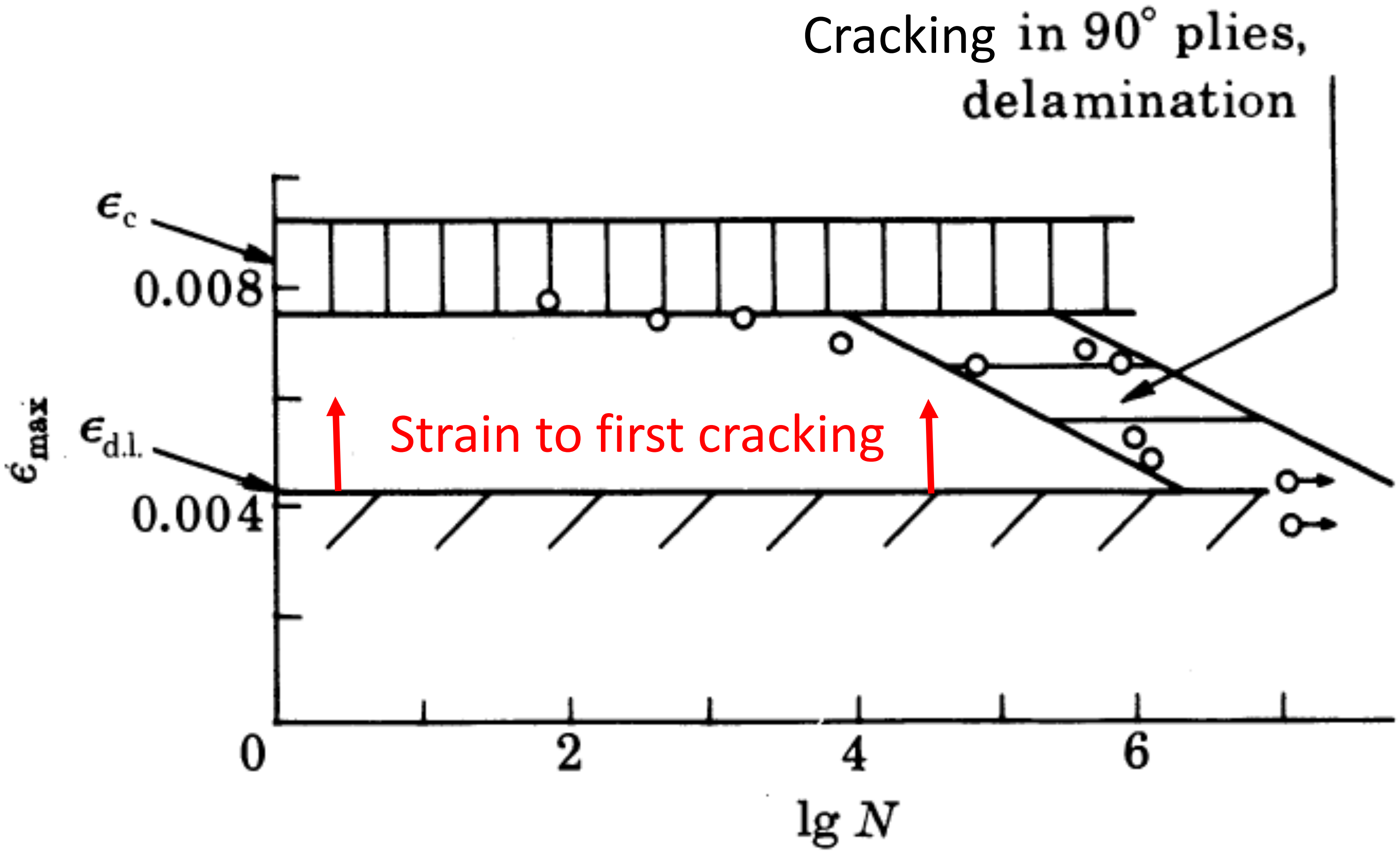
Note:

Strain to initiation of transverse cracking can be increased by increasing stiffness of the “constraining” (0-deg) plies or by decreasing **90-deg ply thickness**

Effect of constraint on evolution of crack density



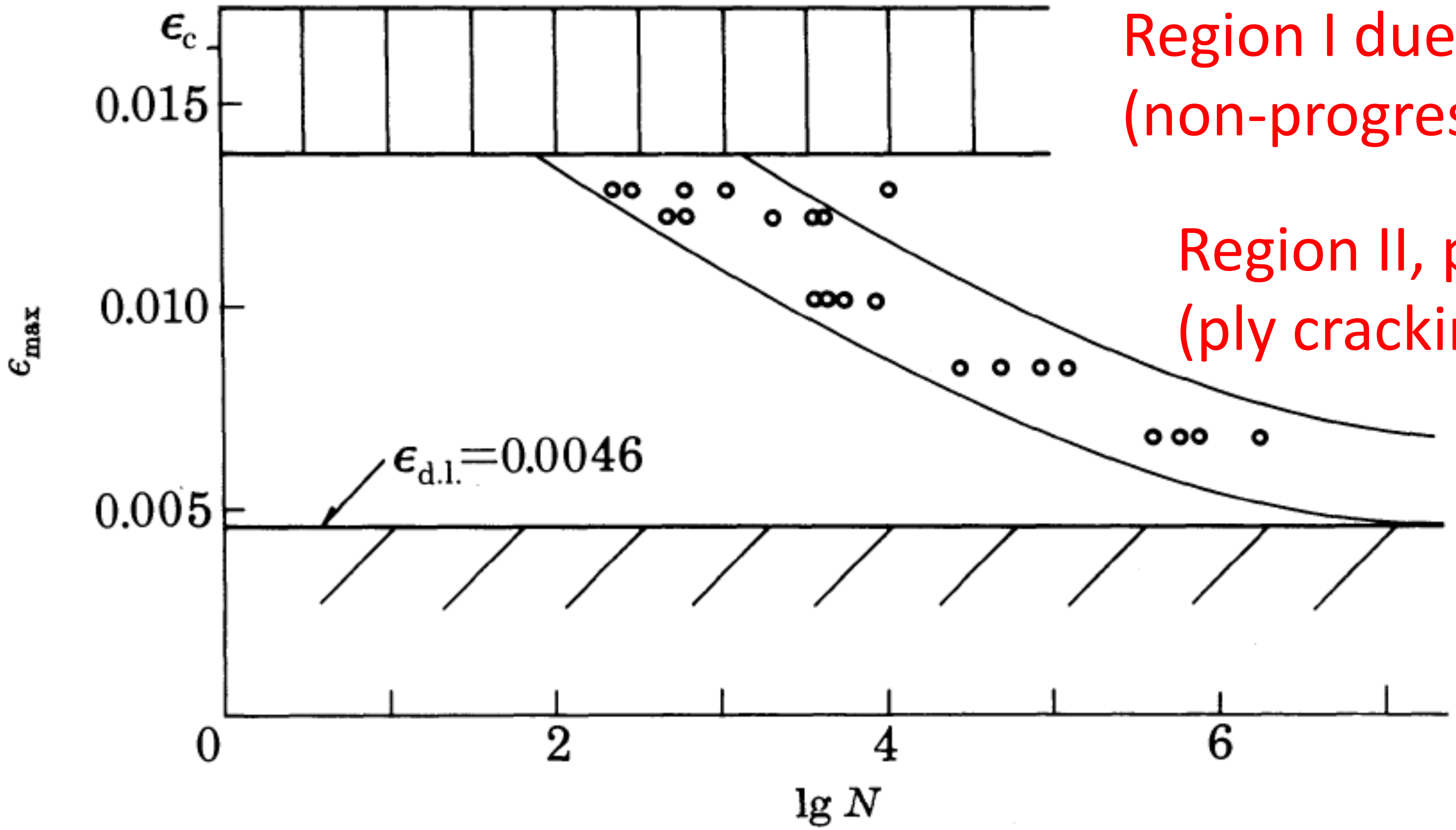
Enhancing the fatigue limit of laminates by increasing the strain to first cracking



Technological solution: Make transverse plies (off-axis plies, generally) thin, thereby suppressing first ply cracking

Is being done!

FLDs of other laminates, $[0/\underline{+}45/90]_s$



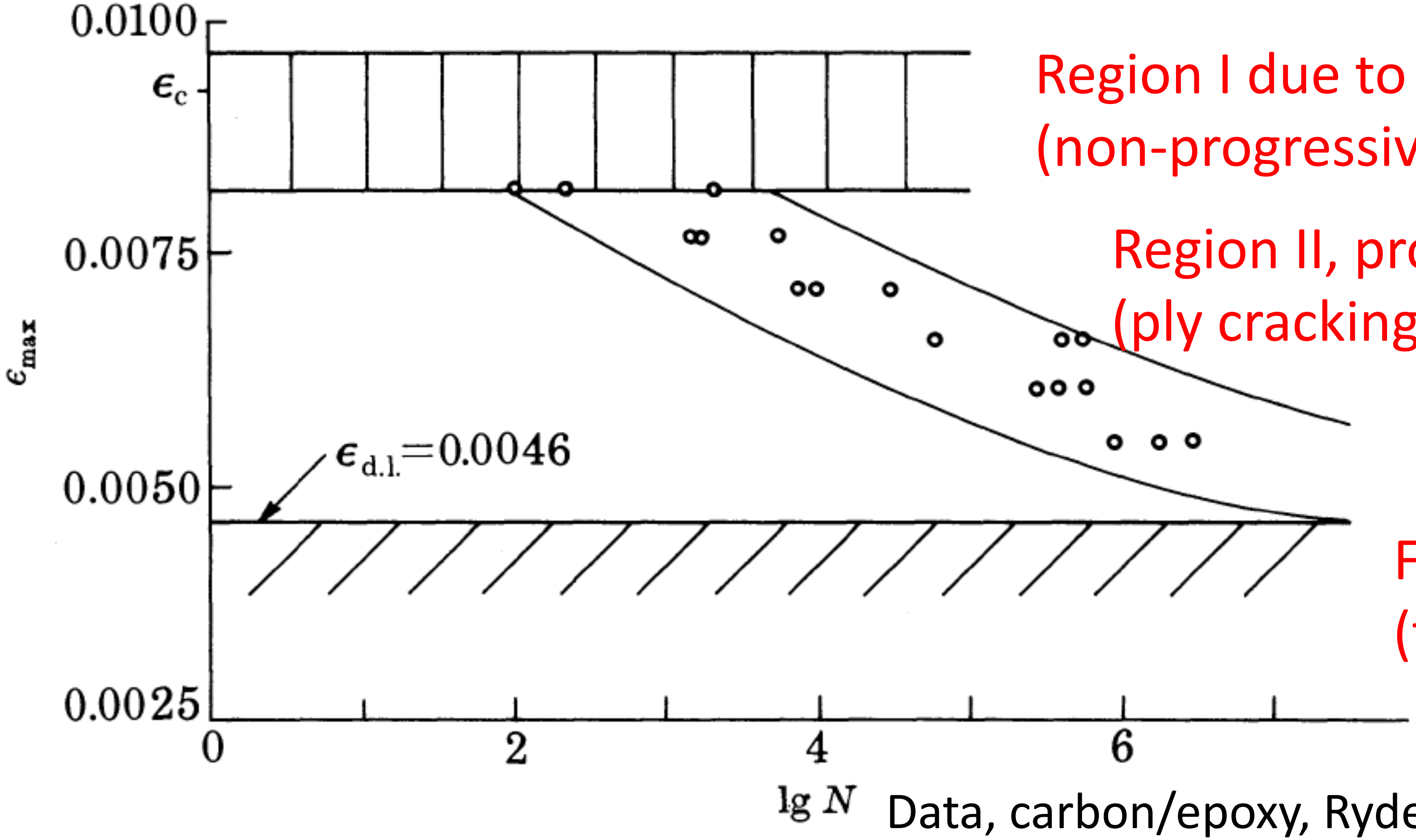
Region I due to 0-deg plies
(non-progressive fiber failure)

Region II, progressive damage
(ply cracking, delamination)

Fatigue limit
(first cracking)

Data: glass/epoxy Hahn and Kim, 1976

FLDs of other laminates, $[0/45/90/-45_2/90/45/0]_s$



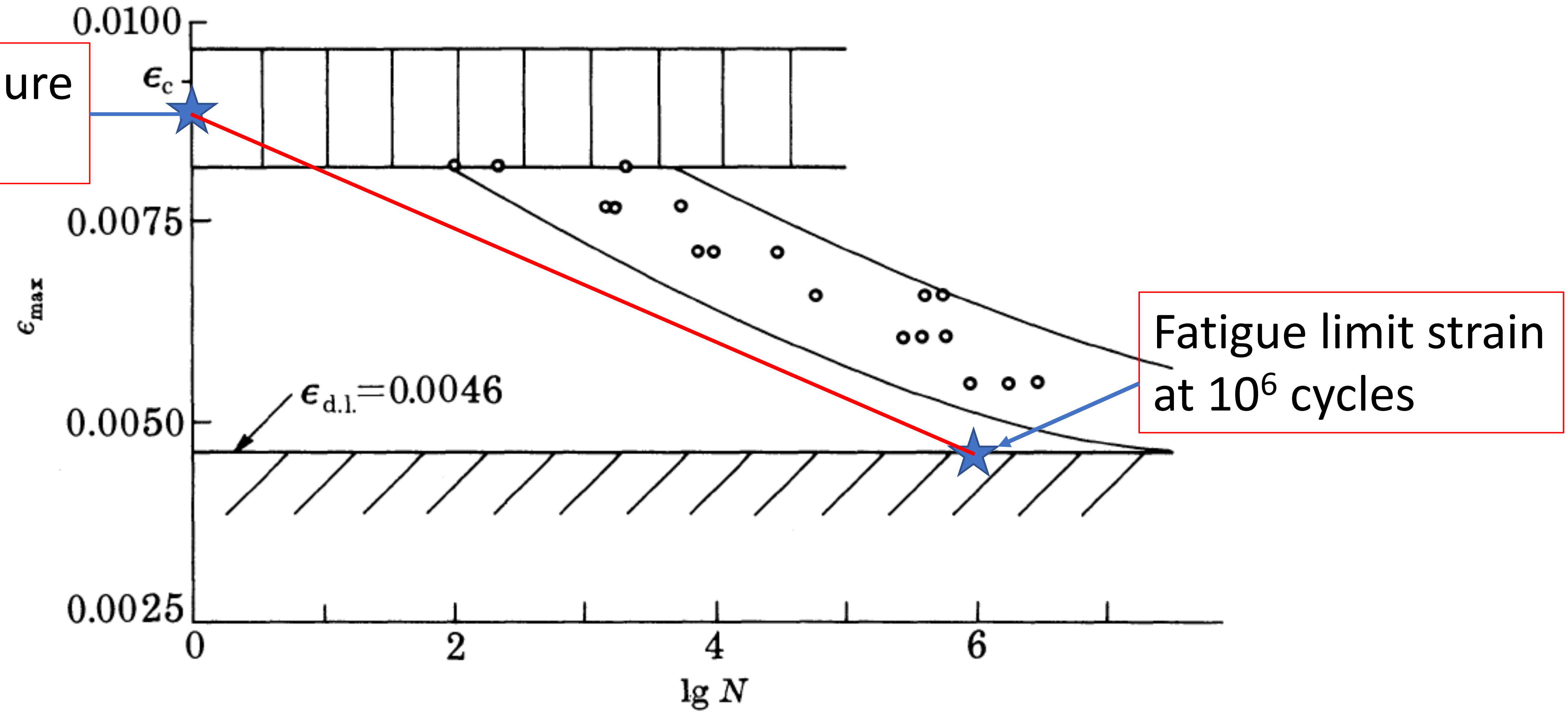
Region I due to 0-deg plies (non-progressive fiber failure)

Region II, progressive damage (ply cracking, delamination)

Fatigue limit (first cracking)

Data, carbon/epoxy, Ryder and Walker, 1977

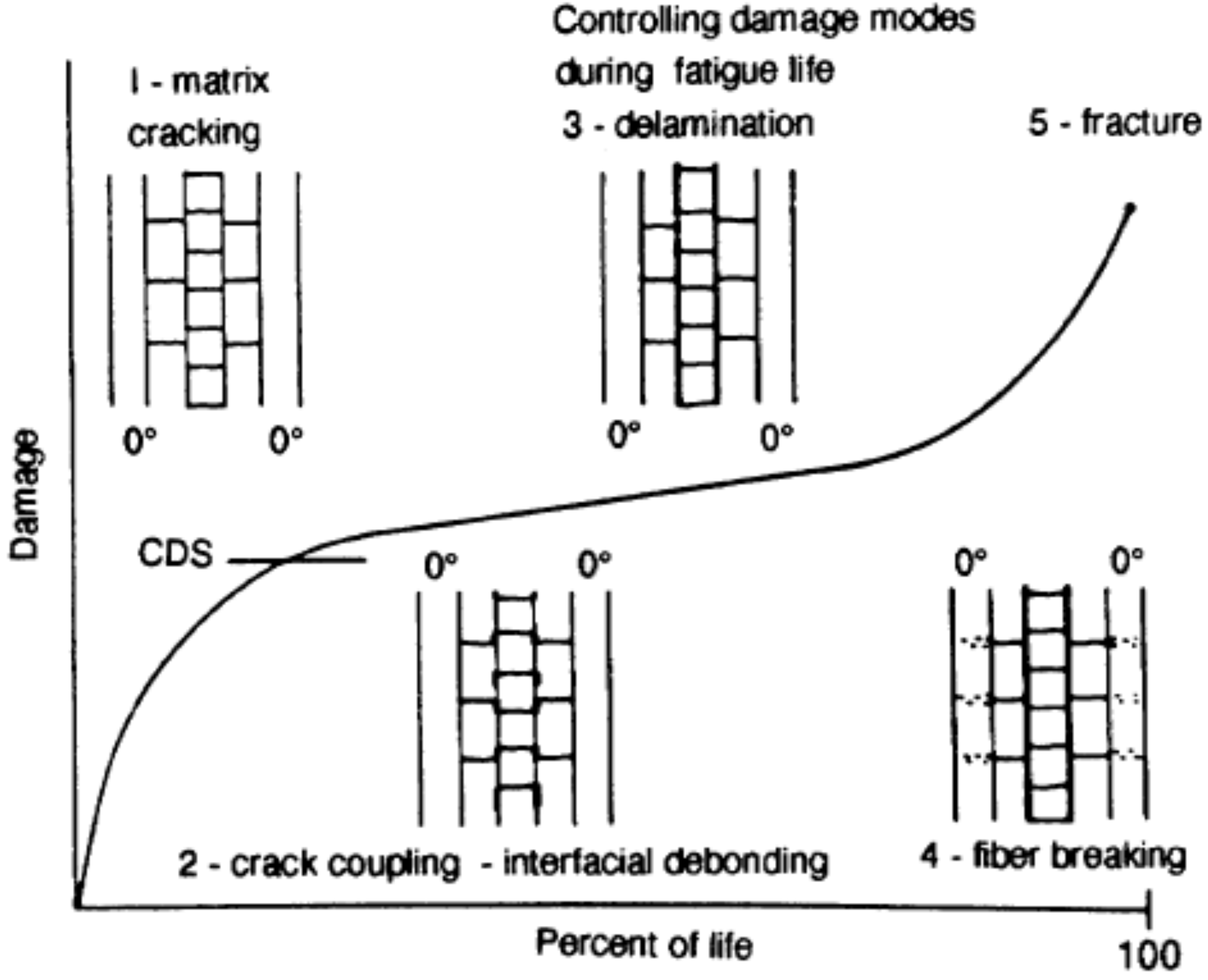
A "quick estimate" procedure for fatigue life of laminates



Fiber failure strain

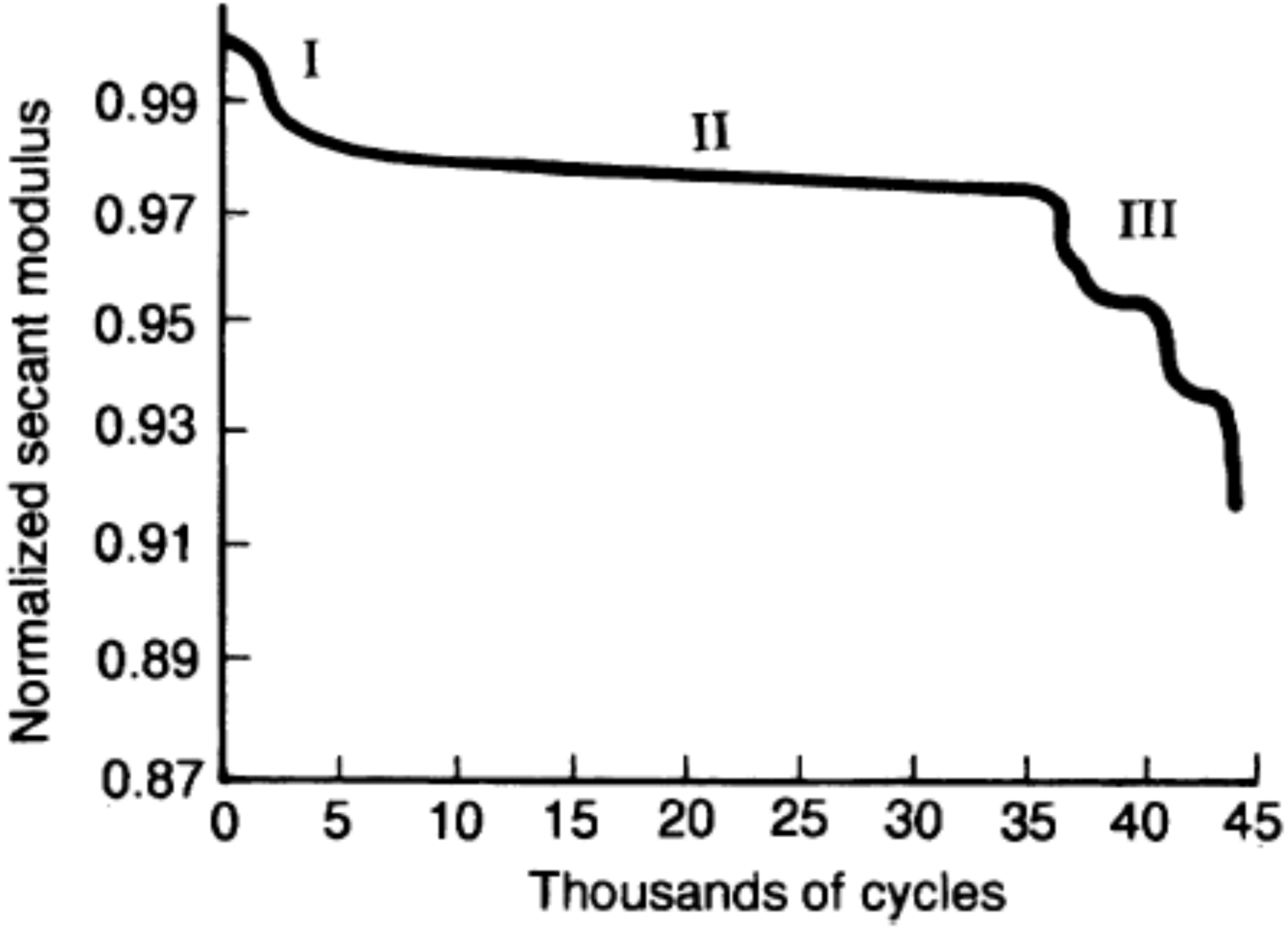
Fatigue limit strain at 10^6 cycles

General features of fatigue damage in laminates



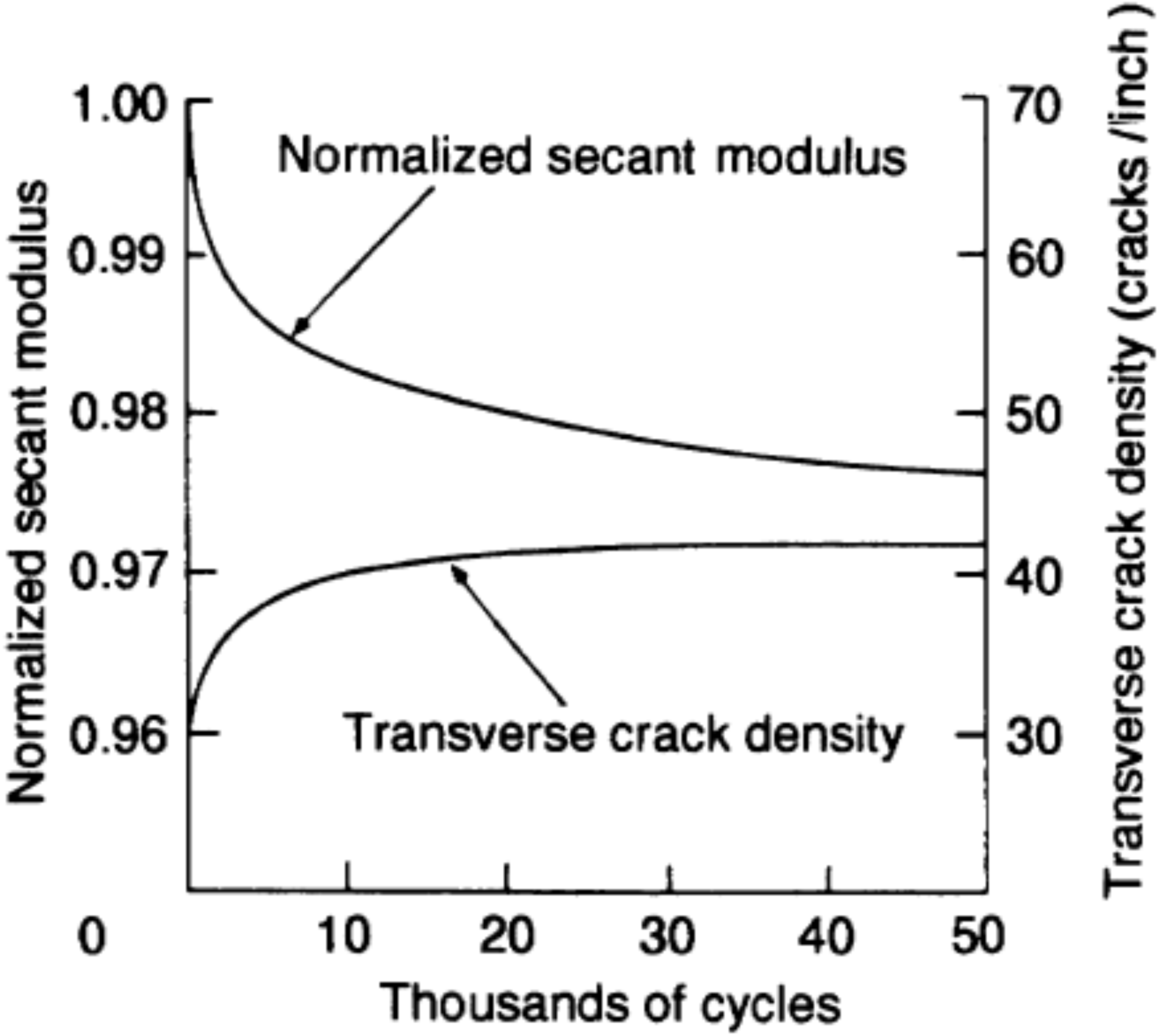
Reifsnider et al, 1983

Stiffness reduction reflecting fatigue damage



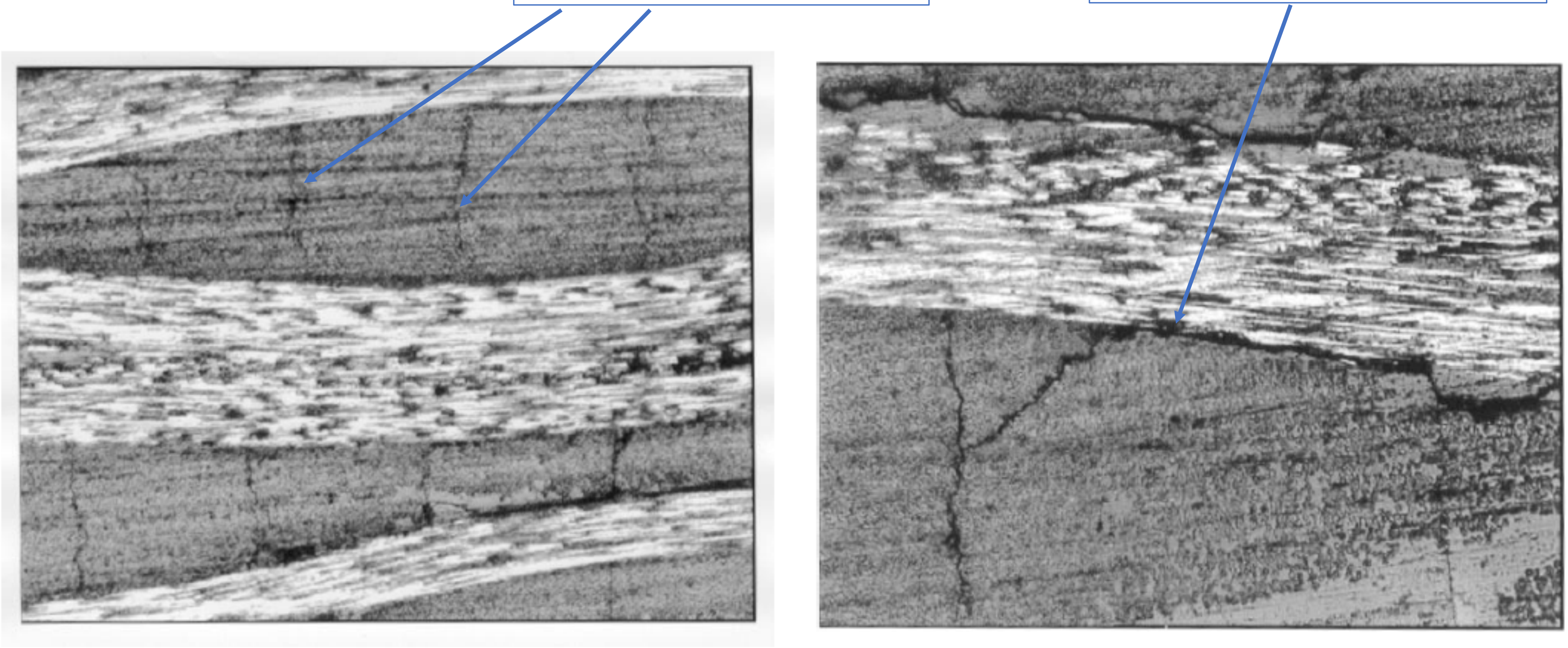
Jamison, et al, 1984

“Critical” state can be stiffness reduction, not “failure by separation”



Jamison, et al, 1984

Other fiber architectures: Woven fabric composites

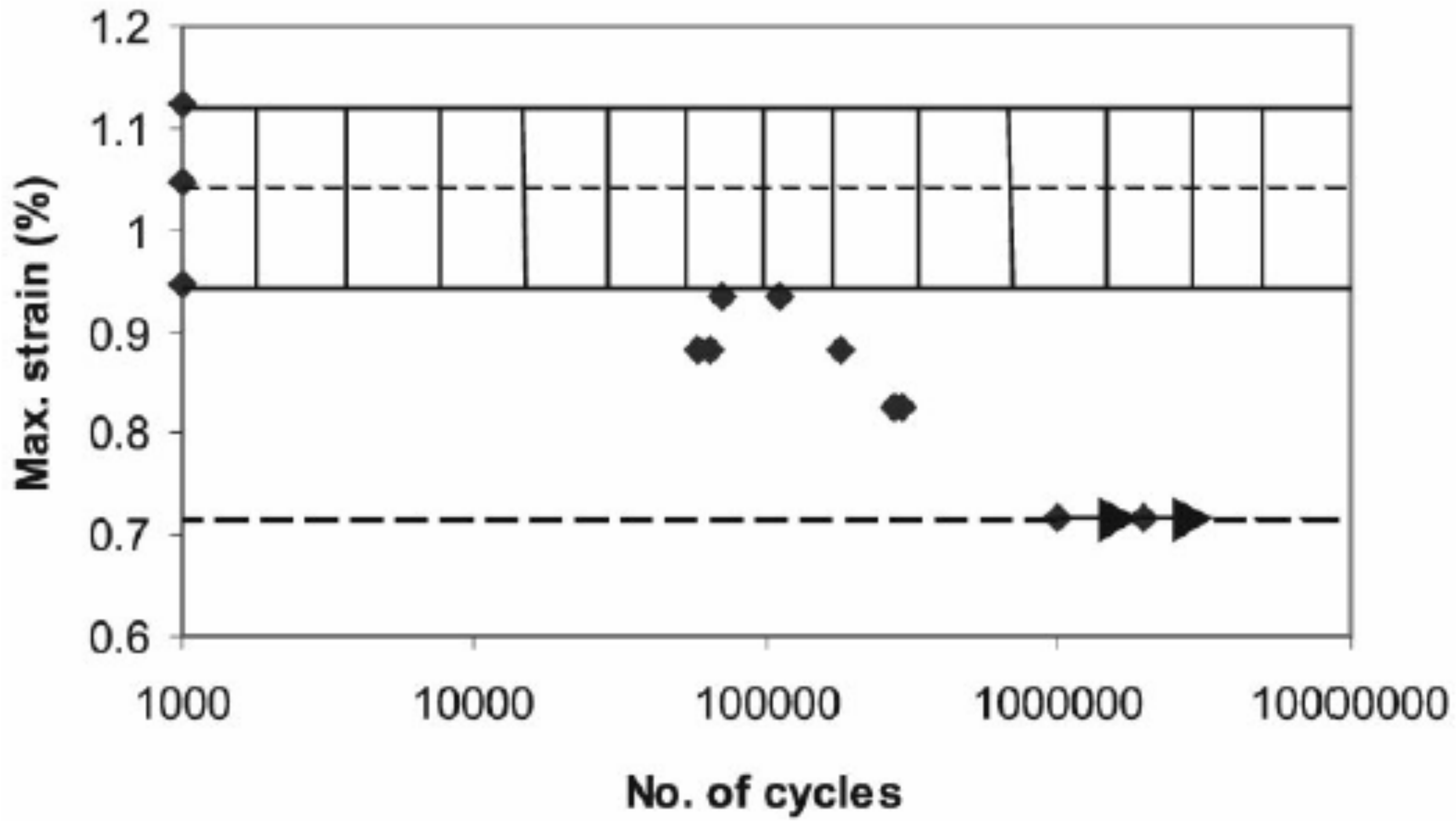


Intra-bundle cracks

Inter-bundle cracking

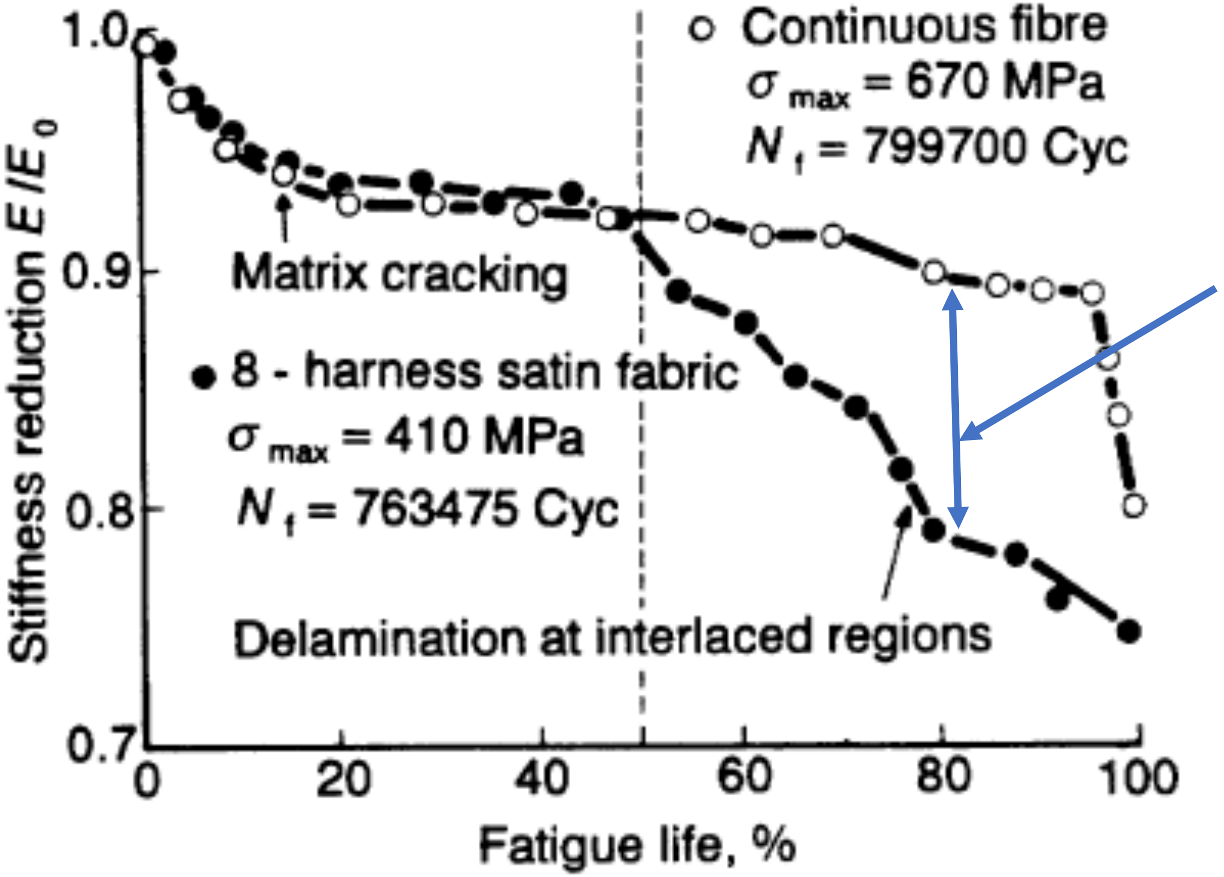
5-harness satin weave carbon/PR500 (Pratt Whitney), Kumar-Talreja, 2000

Fatigue Life Diagram: Woven fabric Composite



5-harness satin weave carbon/PR500 (Pratt Whitney), Kumar-Talreja, 2000

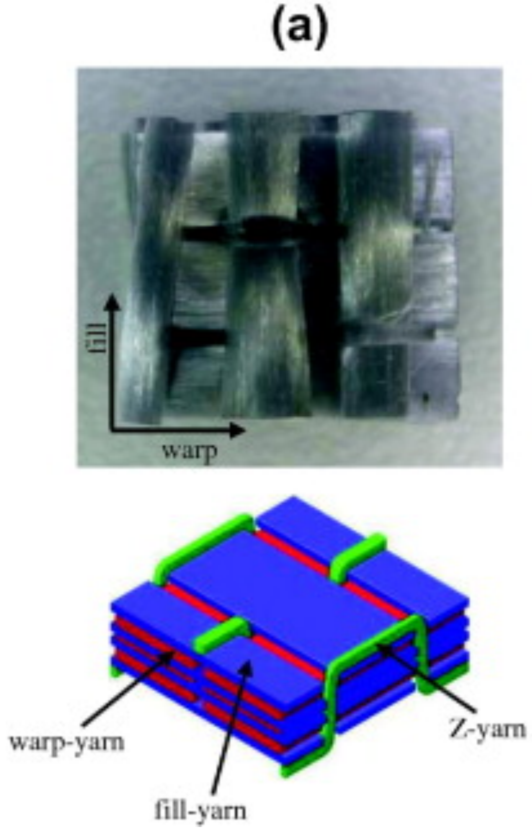
Fatigue damage, continuous fiber vs. woven fabric composites



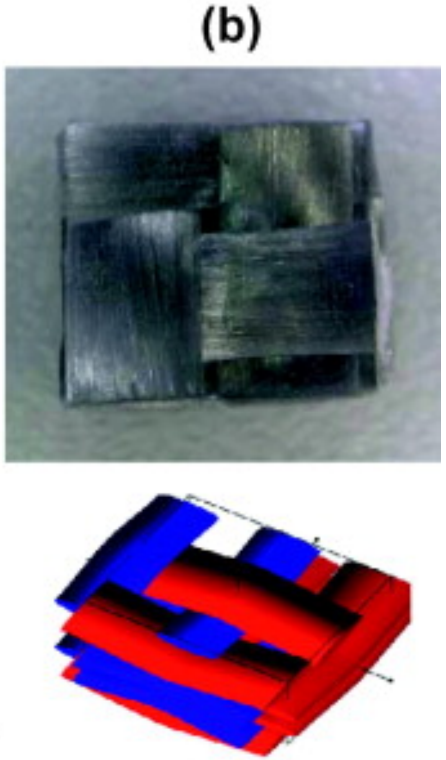
Additional degradation due to more extensive delamination in woven fabric composites

Schulte et al, 1987

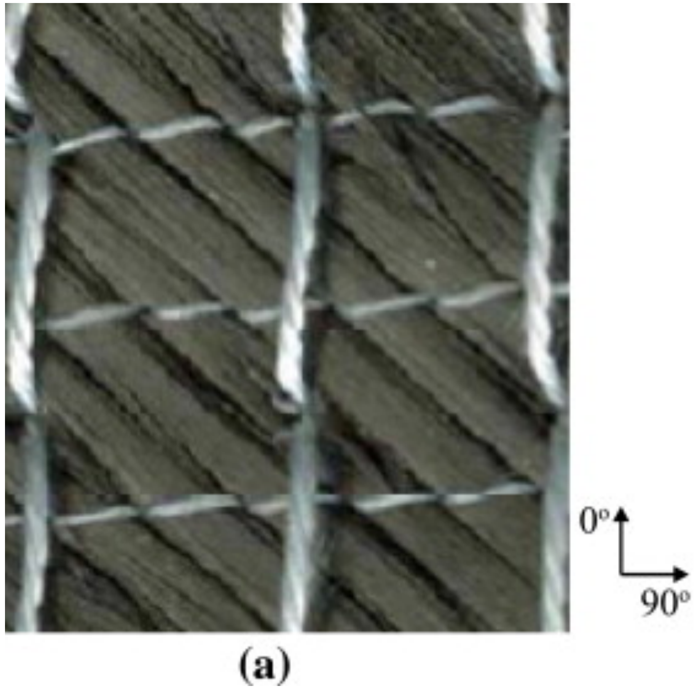
Fiber architectures driven by cost



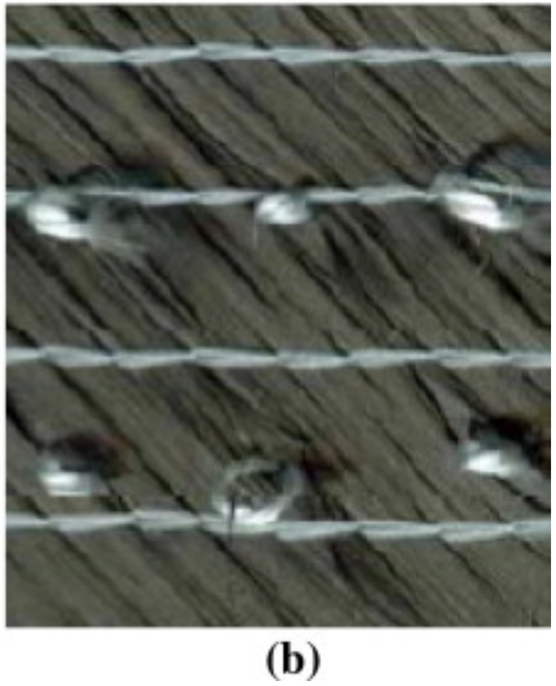
Non-crimp 3D orthogonal weave, E-glass



Plane weave, E-glass



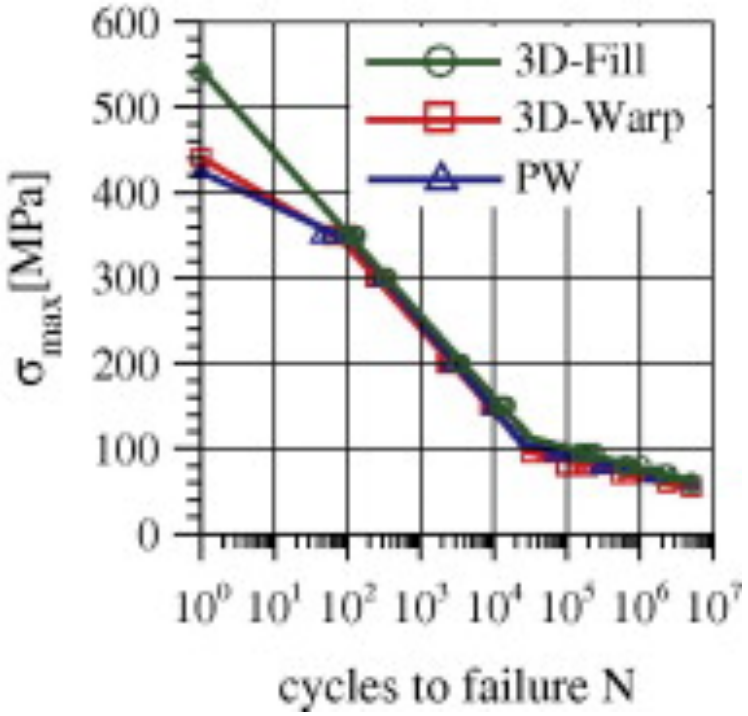
Non-crimp, unstitched, carbon

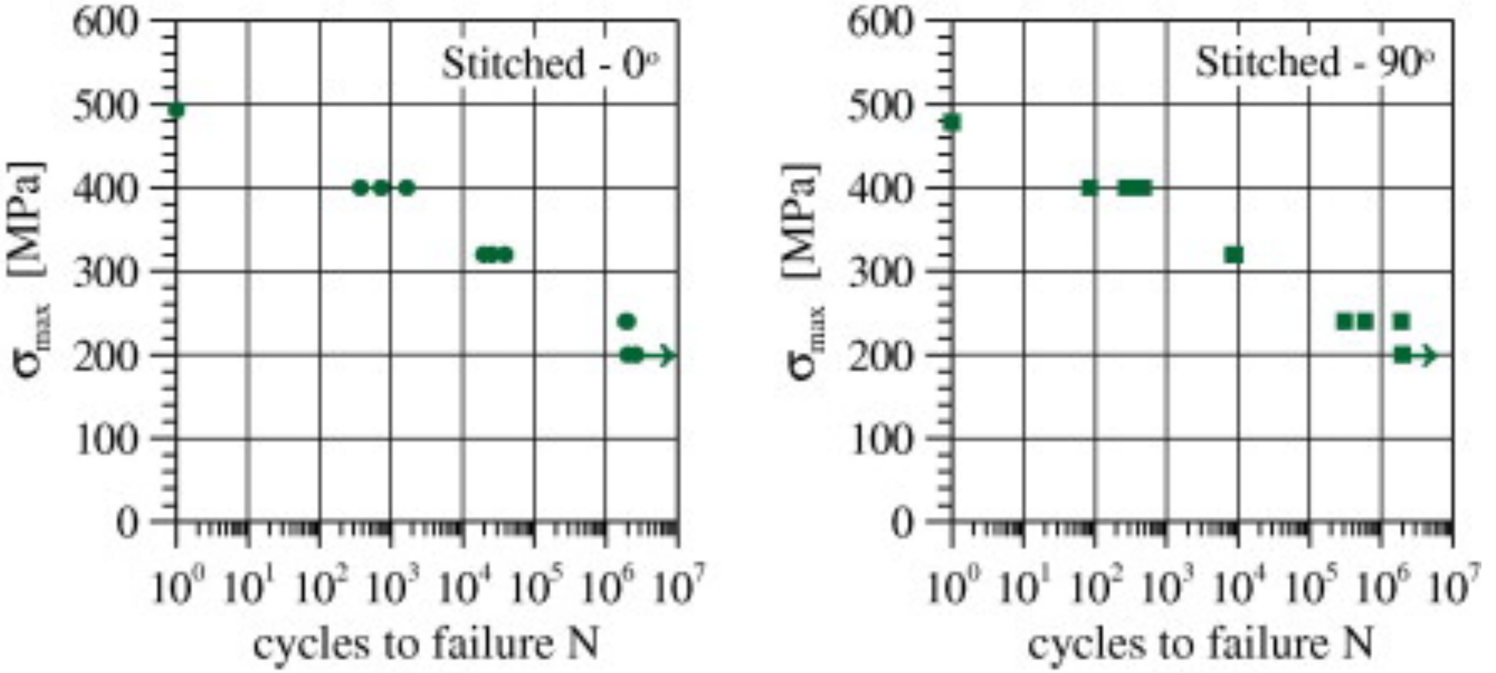


Non-crimp, stichted, carbon

Carvelli et al, 2010

Fatigue life trends





(a) (b)

Data, Carvelli et al, 2010

Preliminary observations:

1. Fatigue life in fiber direction not sensitive to fiber architecture
2. Stitching makes it worse by introducing stress concentrations

Summary: One important message

- It is widely believed that fatigue of composite laminates is “complicated”, and that “too many parameters” exist. “Changing anything changes the fatigue behavior”.

Not true! Some basic observations and looking for answers to basic questions can simplify the fatigue problem. Not doing so can lead to empirical approaches that require a lot of data and still unreliable predictions.