

FATIGUE OF *ENGINEERED* METALLIC MATERIALS UNDER CONSTANT - AND VARIABLE - AMPLITUDE LOADING

J. C. Newman, Jr.

Fatigue & Fracture Associates, LLC

Emeritus Giles Professor

Former Richard Johnson Chair

Department of Aerospace Engineering

Mississippi State University

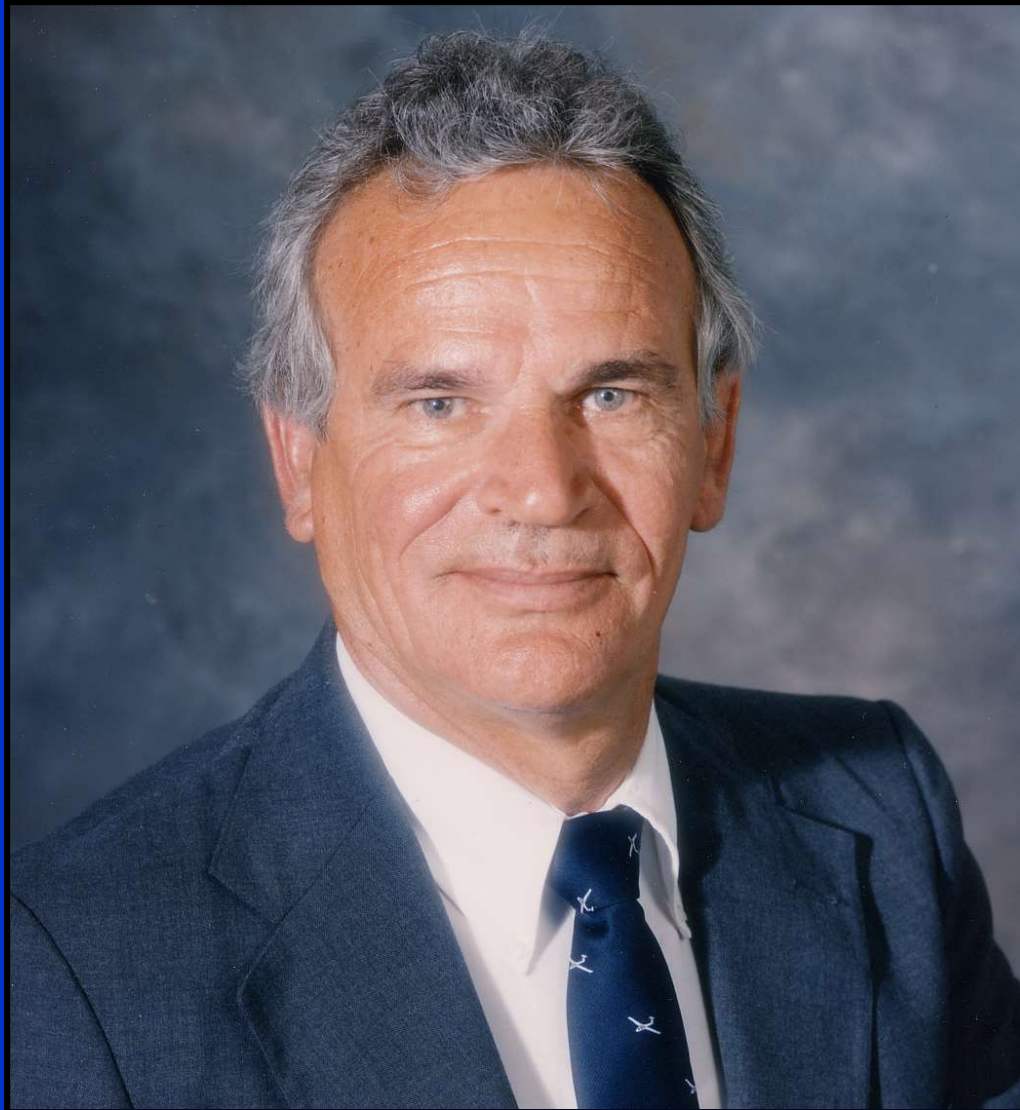
Mississippi State, MS, USA

InSIS Seminars on Structural Integrity

6 November 2020



Dr. Wolf Elber



1941 - 2019

NASA LANGLEY RESEARCH CENTER CIRCA 1970



“Dawning of a new age in crack-growth methodology”

Materials Division & Fatigue and Fracture Branch - 1985



A Rational Analytic Theory of Fatigue

PAUL C. PARIS
Assistant Professor of Civil Engineering



P. C. Paris

*Paul C. Paris
2/12/2010*



M. P. Gomez

MARIO P. GOMEZ* and WILLIAM E. ANDERSON
Research Engineers, Boeing Airplane Company



W. E. Anderson

The Trend in Engineering, January 1961

Boeing (?-1963)
NASA LaRC (1963-66)
OSU (1966-?)

$$da/dN = f(K_{\max}, R)$$

~1970: LEFM analyses could “*not*” predict S-N behavior.

Why?

Fracture Mechanics Developments to make Fatigue-Life (S-N; ϵ -N) Analyses Work for *Engineered* Metallic Materials

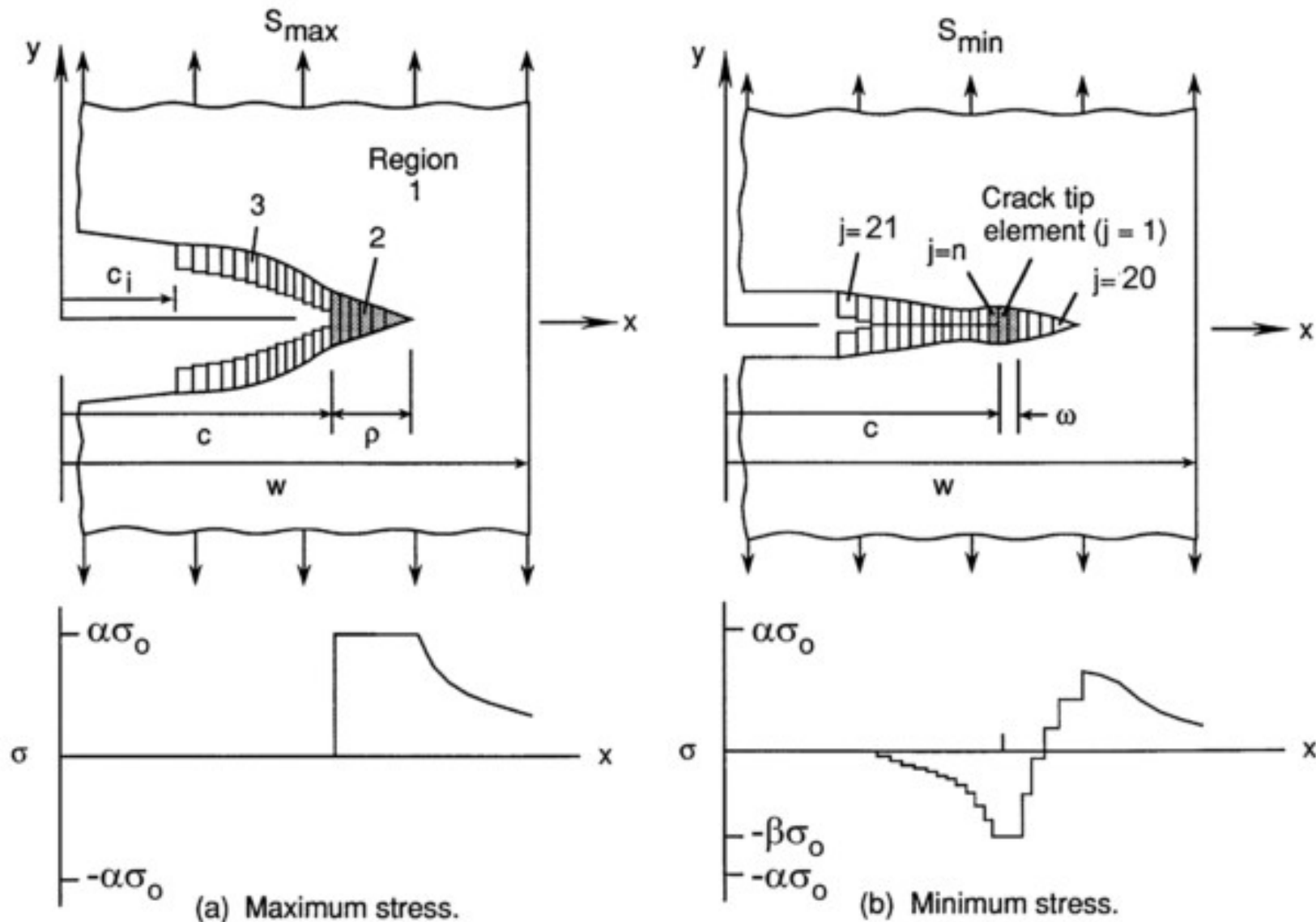
- Stress-intensity factors for surface cracks
- Crack-closure theory ($\Delta K_{\text{eff}} - da/dN$)
- Nonlinear fracture mechanics
- Small-crack behavior
- Material & machining micro-structural features

Fracture Mechanics Developments to make Fatigue-Life (S-N; ϵ -N) Analyses Work for *Engineered* Metallic Materials

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FASTRAN – Crack-Growth and Closure Model

(Modified Dugdale Model; Newman 1976 - present)



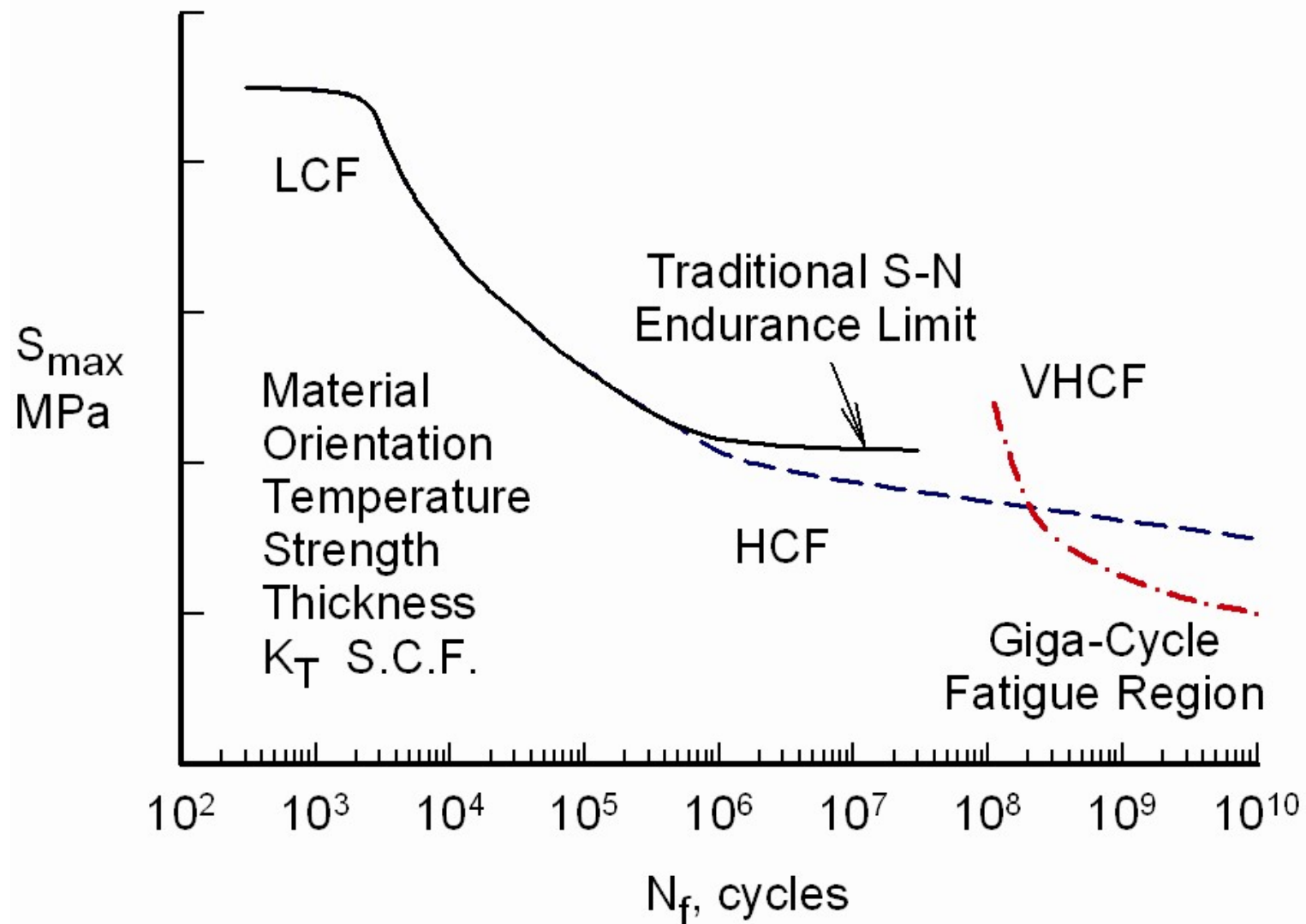
Some Important Features of *FASTRAN*

- Plane-strain to plane-stress constraint-loss behavior (**needed for spectrum loading**)
- Cycle-by-cycle life calculations (**NMAX = 1**)
(1976: **1 cycle, 7 sec**; 2015: **~1,000 cycles/sec**)



- Rainflow or other cycle counting methods are “**not**” needed — “**Rainflow-on-the-Fly**” methodology is used in *FASTRAN*

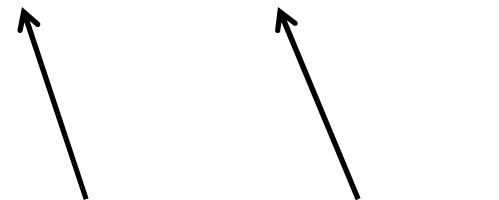
Stress-Life (S-N) Behavior from LCF to UHCF



Total Fatigue Life by Crack Propagation

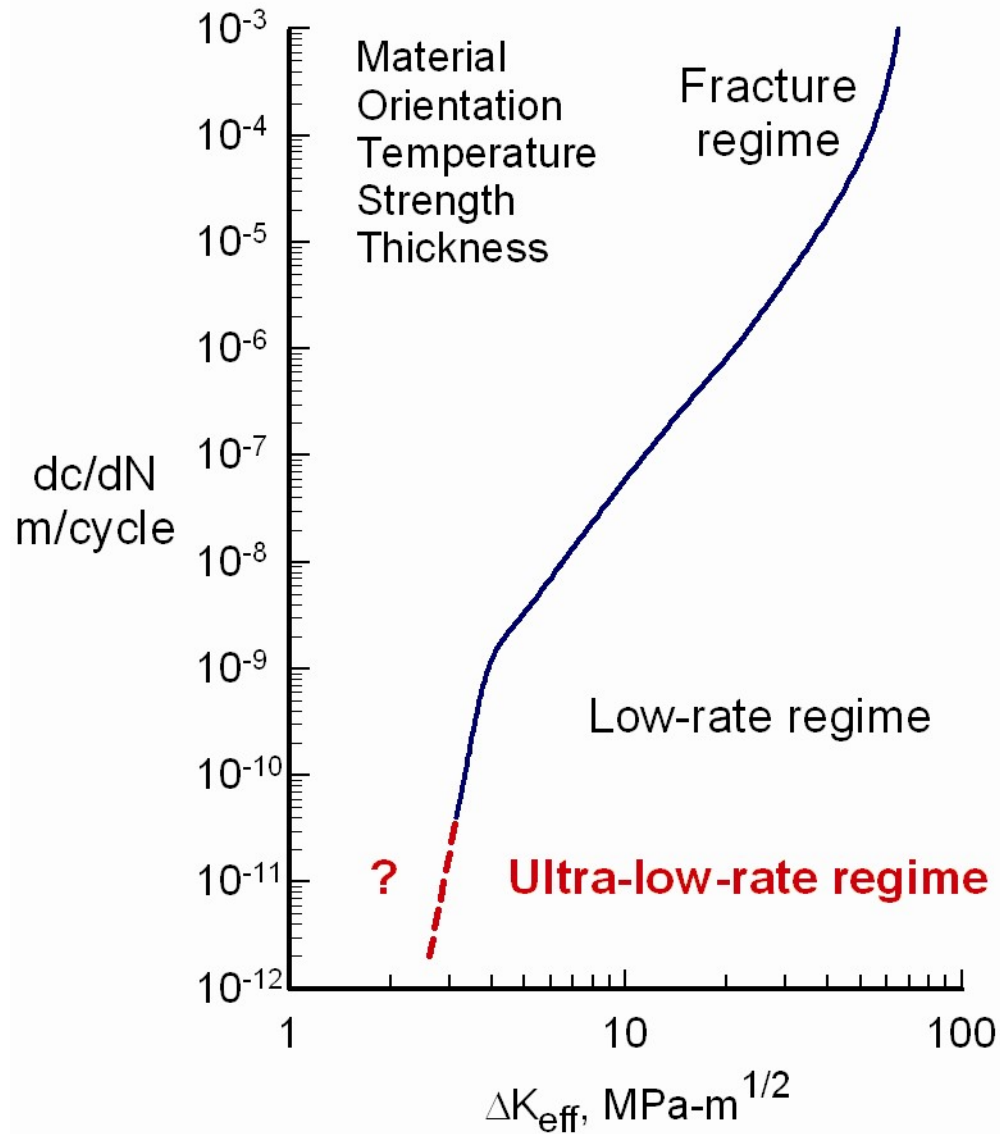
“Engineered” materials

$$N_f = N_i + N_{cp}$$

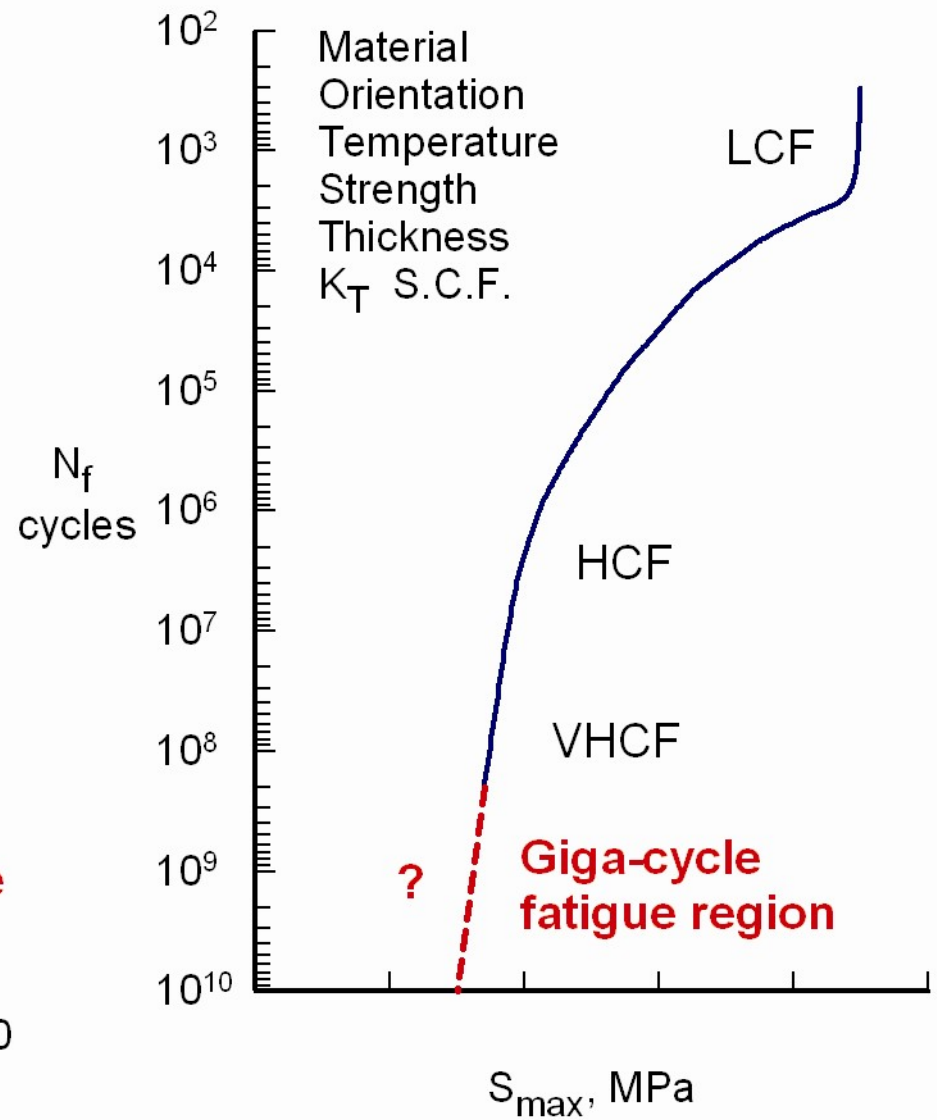
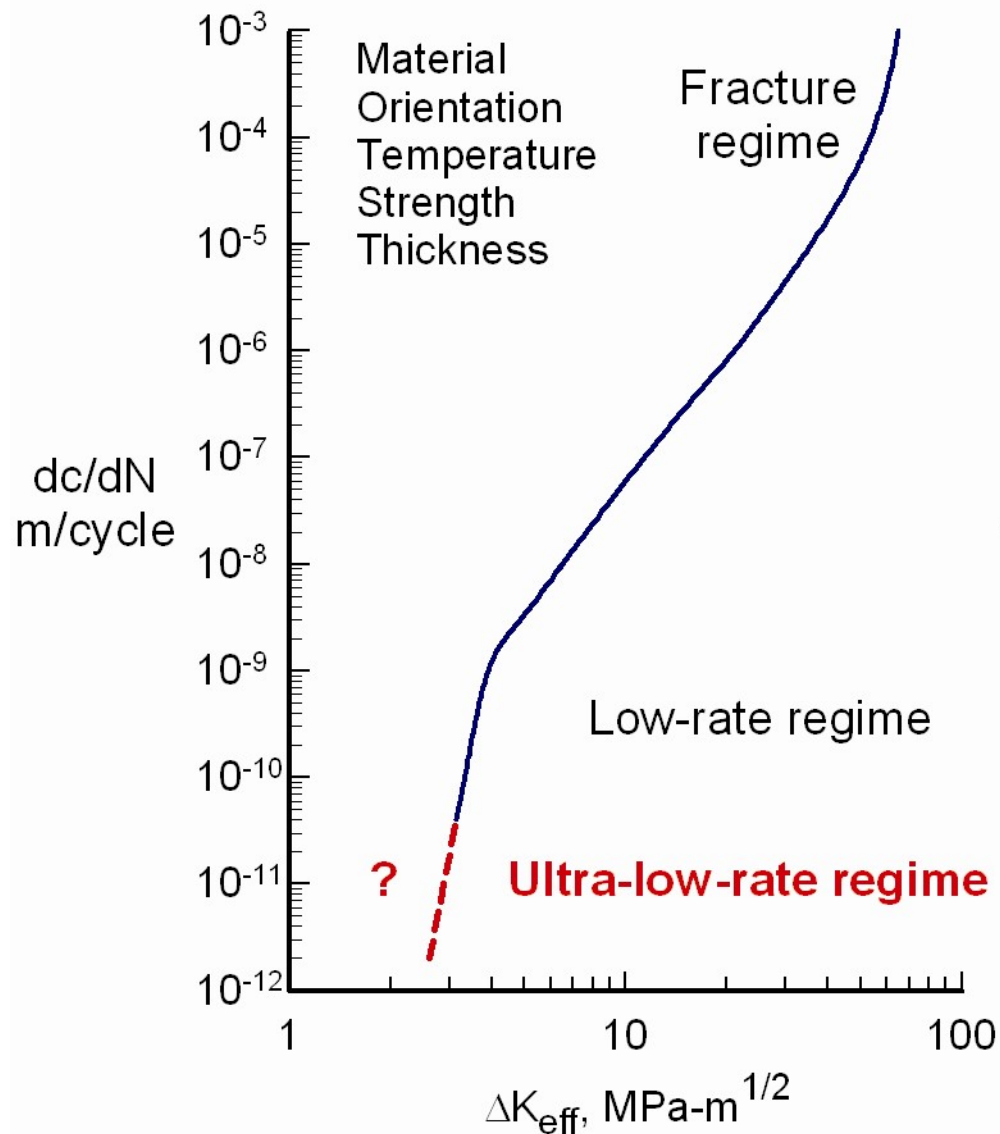

NLFM **LEFM**

- Nucleation is crack propagation from micro-crack growth
- **NLFM** – non-linear fracture mechanics (small cracks)
- **LEFM** – linear elastic fracture mechanics (large cracks)

STRESS-LIFE BEHAVIOR IS DIRECTLY RELATED TO FATIGUE-CRACK GROWTH RATES FOR MANY MATERIALS



STRESS-LIFE BEHAVIOR IS DIRECTLY RELATED TO FATIGUE-CRACK GROWTH RATES FOR MANY MATERIALS



Outline of Presentation

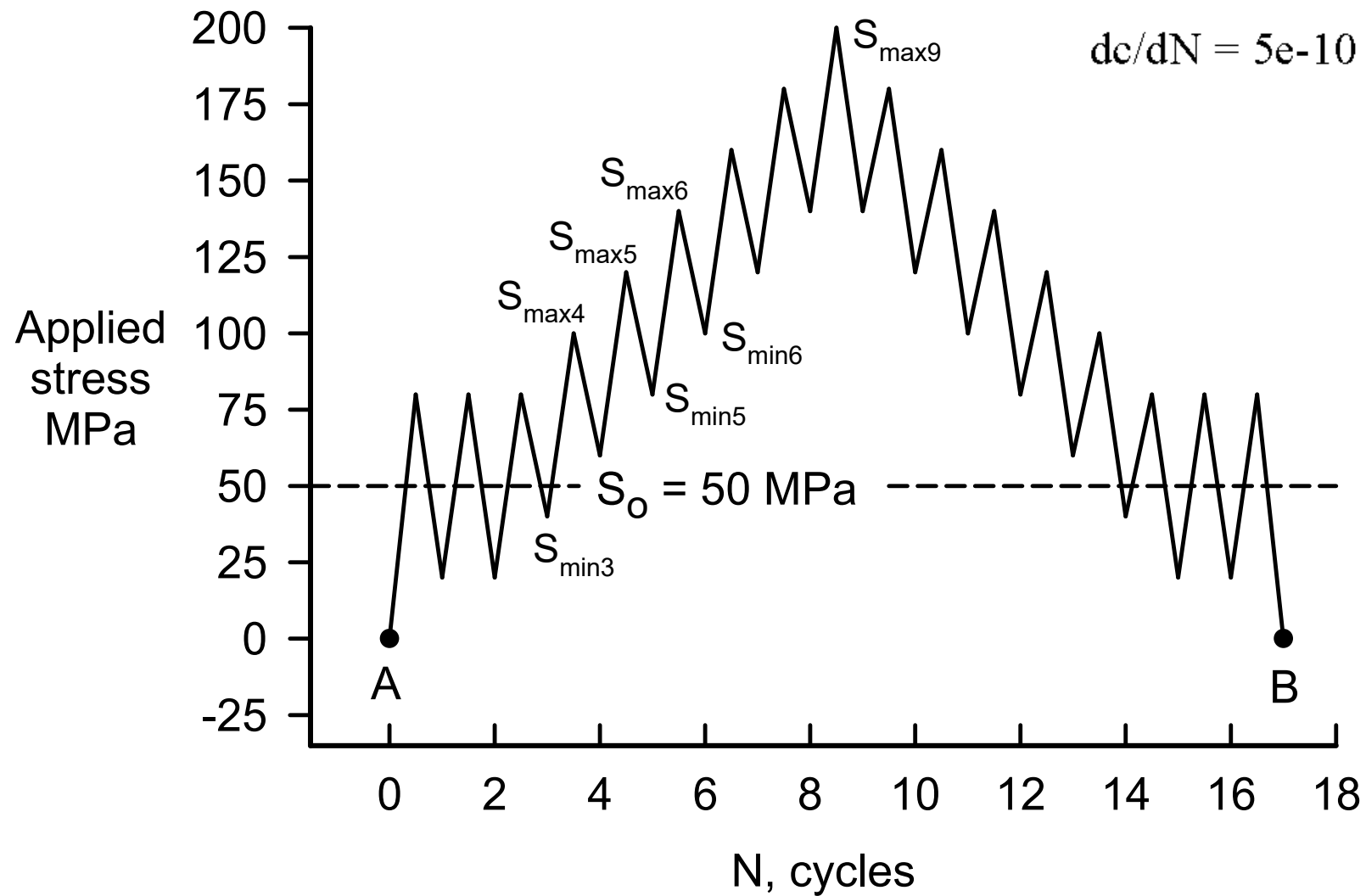
- *Rainflow-on-the-Fly* methodology (FASTRAN subroutine)

Rainflow on the Fly

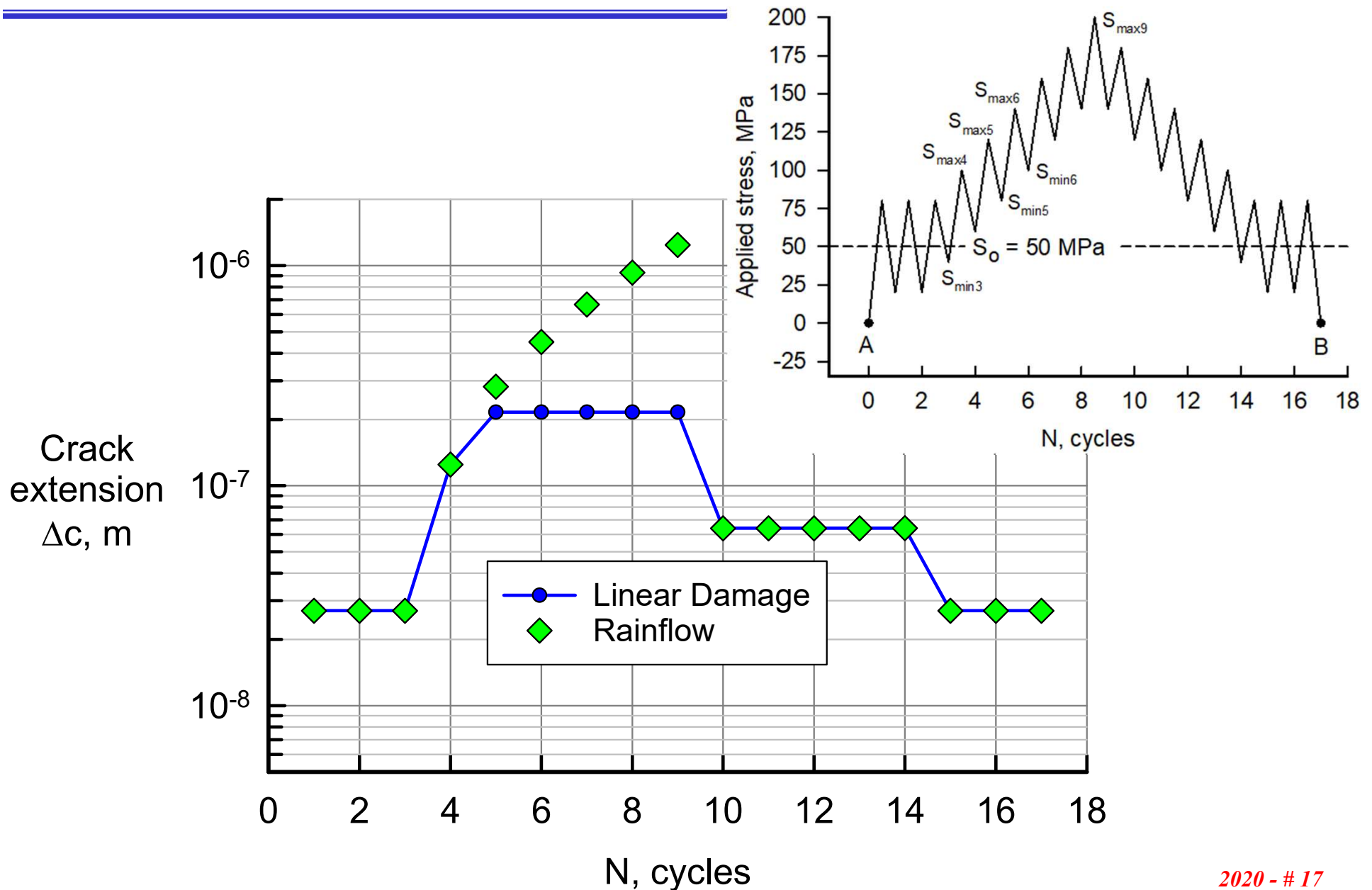


Damage is a function of current loading and load history ...

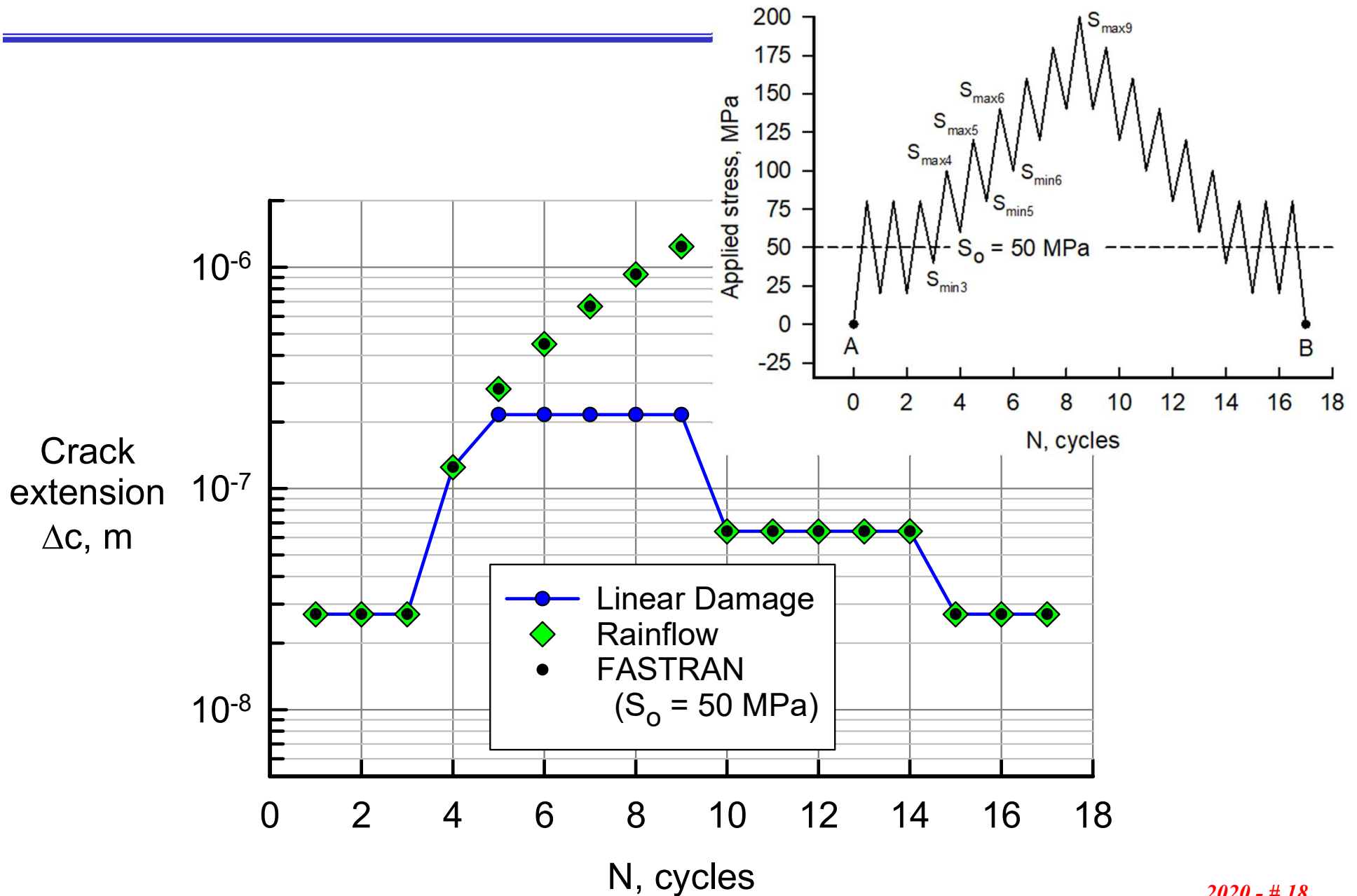
Christmas-Tree Loading with Constant Crack-Opening Stress



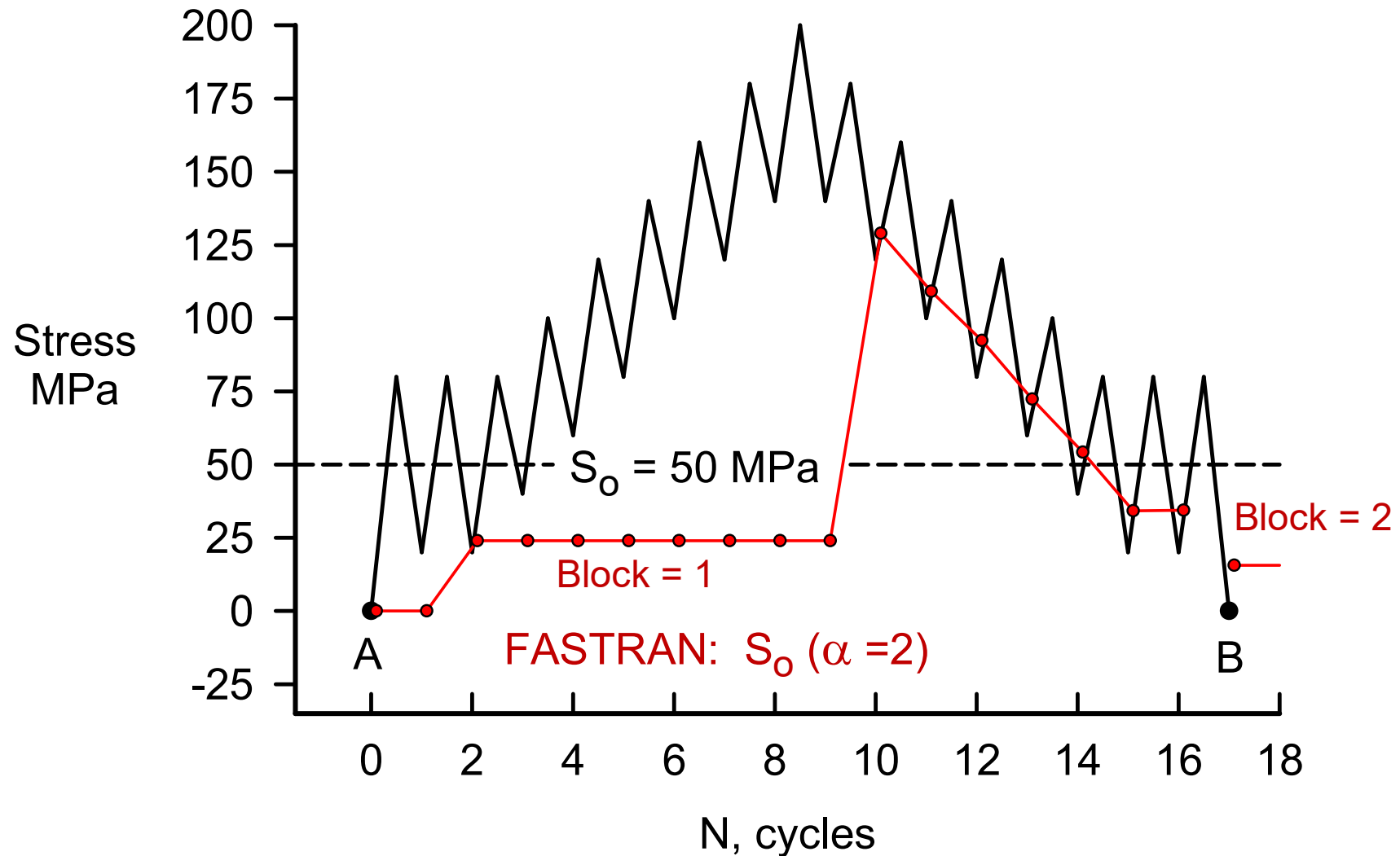
Crack Extension for Each Cycle under X-mas Tree Loading



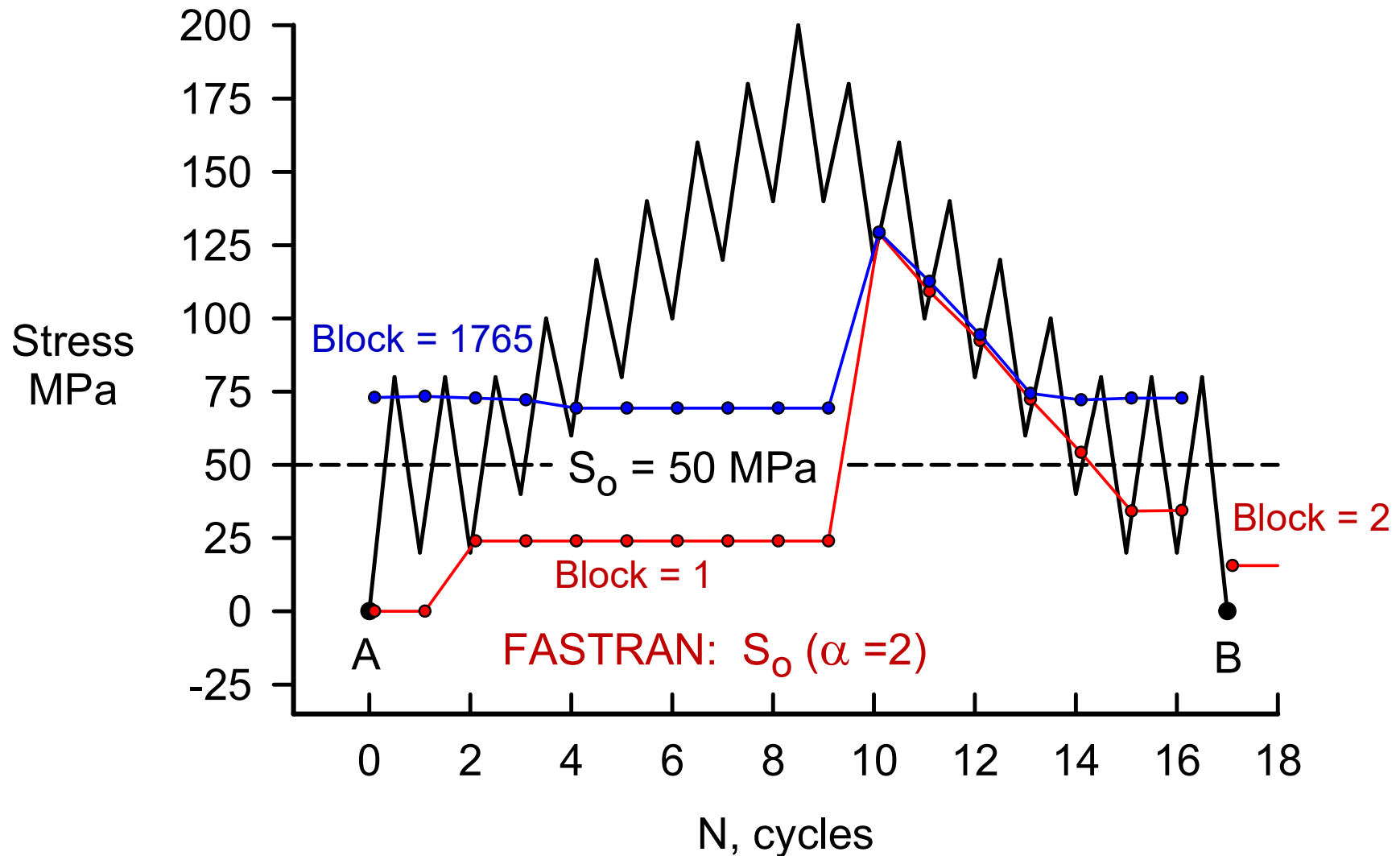
Crack Extension for Each Cycle under X-mas Tree Loading (2)



Full Crack-Closure Model after One Block of Loading



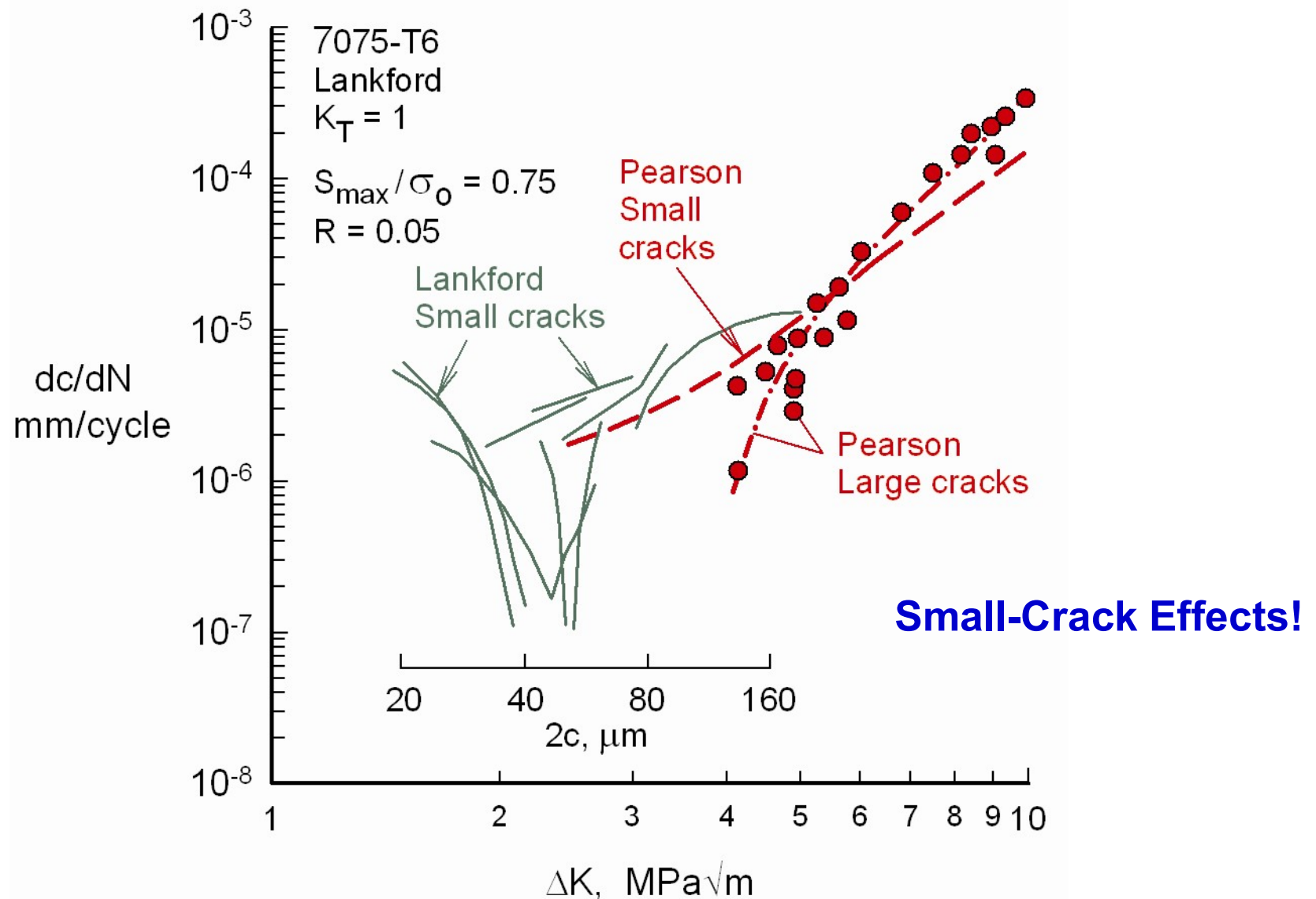
Full Crack-Closure Model after Many Blocks of Loading



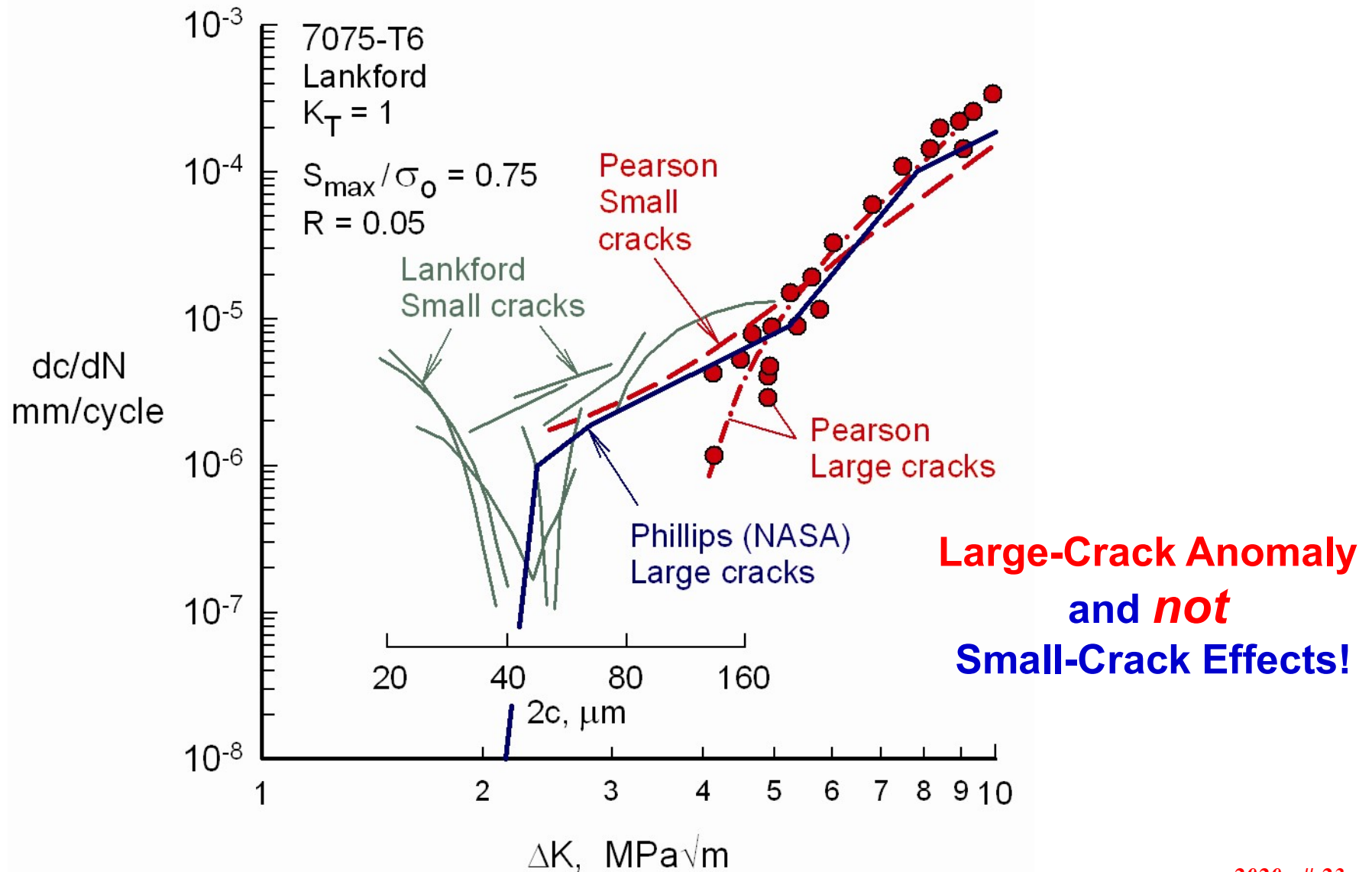
Outline of Presentation

- *Rainflow-on-the-Fly* methodology (FASTRAN subroutine)
- **Small-Crack Programs**

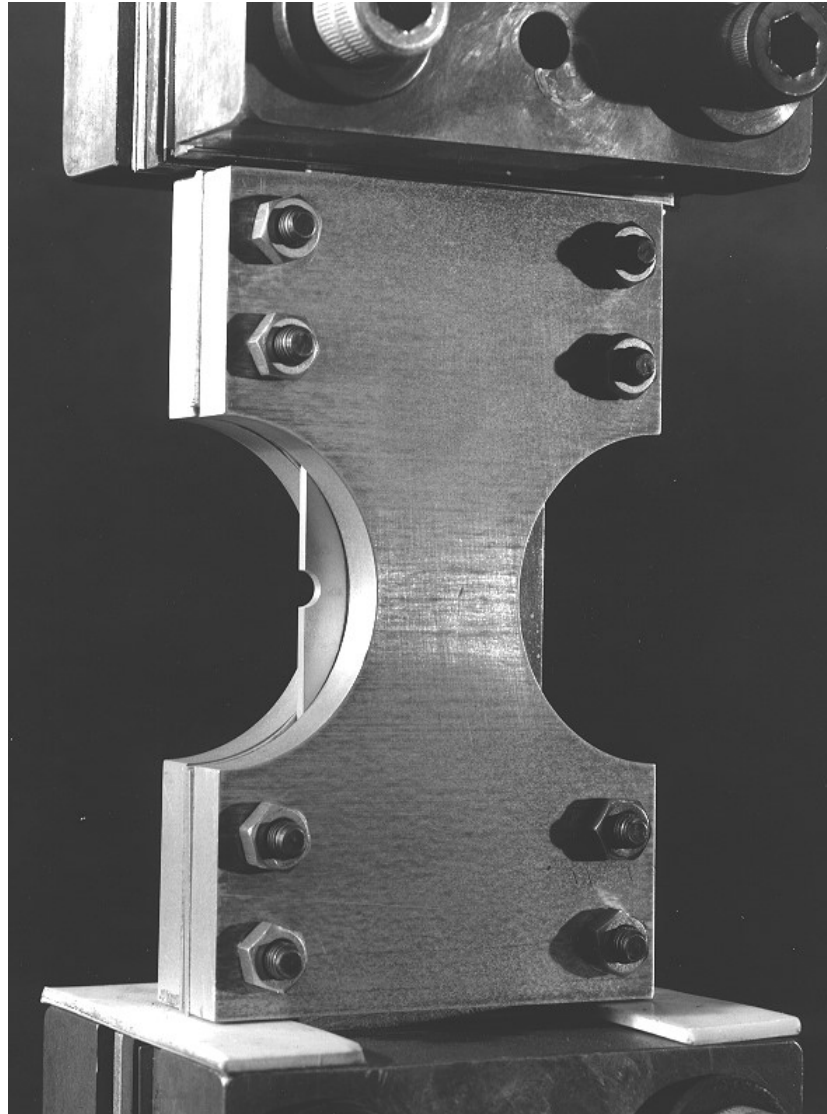
Pearson's Small-Crack Data (1975) Initiated a World-Wide Study by Many Research Organizations



Comparison of Small- and Large-Crack Data

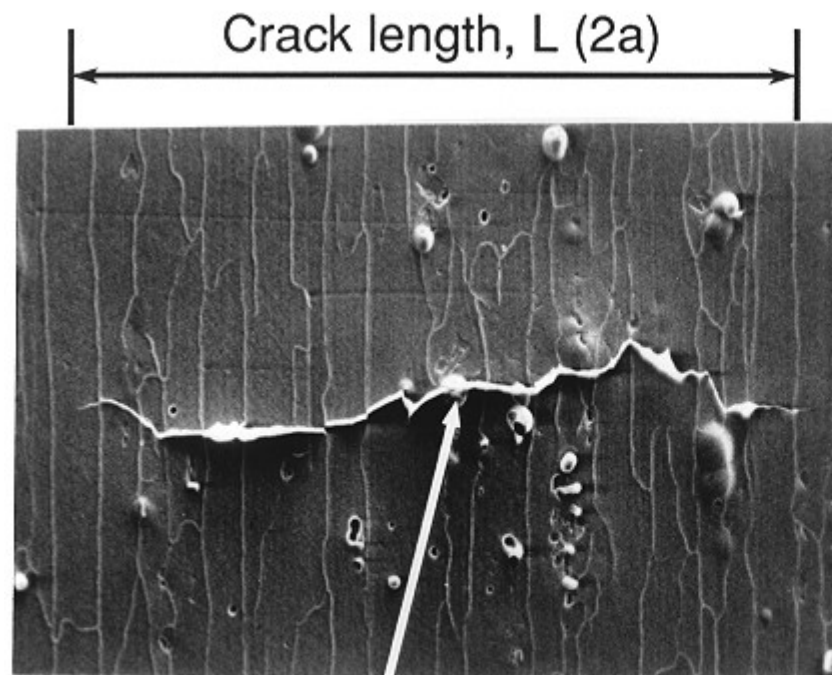


AGARD Small-Crack Test Specimen



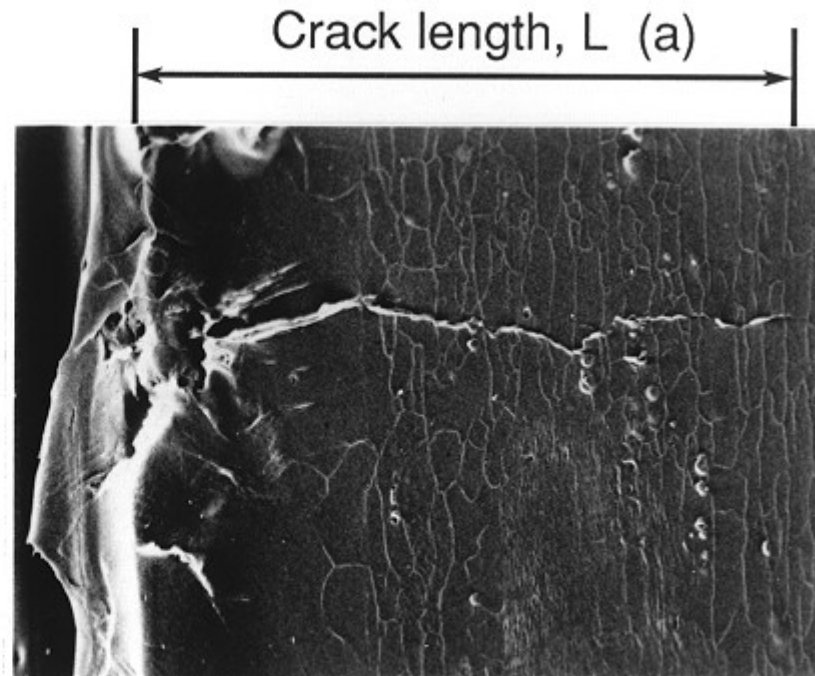
Crack Initiation Sites at Notch Root

7075-T6 and LC9cs Aluminum Alloys (1987-1993)



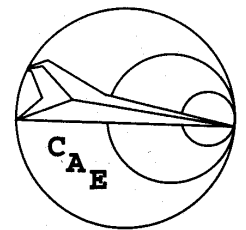
(a) 7075-T6

$a \approx 90 \mu\text{m}$



(b) LC9cs (7075 clad)

$a \approx 180 \mu\text{m}$



SMALL-CRACK TEST AND ANALYSIS PROGRAMS

1982, 1984-1994

AGARD SMP Symposium on Short-Crack Behaviour (1982) – H. Zocher

AGARD R-732, R-767 – P.R. Edwards and J.C. Newman, Jr.

AGARD R-766 – A.J. Mom and M.D. Raizenne

AGARD R-766 (Addendum) – T. Pardessus, E. Jany and M.D. Raizenne

NASA/CAE RP-1309 – J.C. Newman, Jr. and X.R. Wu

Materials

2024-T3

7075-T6

Lc9CS (7075-T6 clad)

2090-T8E41

4340 Steel

Ti-6Al-4V

IMI-685

Ti-17

Loading Actions*

Constant amplitude ($R = -2$ to 0.5)

FALSTAFF (fighter spectra)

Inverted FALSTAFF

Gaussian ($R = -1$ random spectra)

TWIST (transport spectra)

Mini-TWIST

Felix-28 (helicopter spectra)

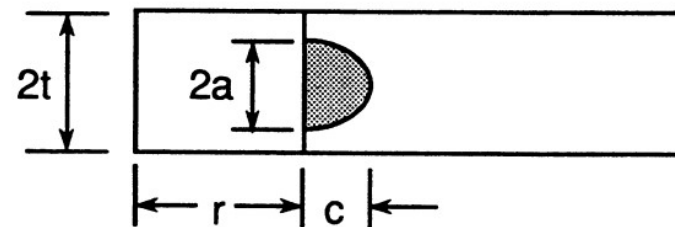
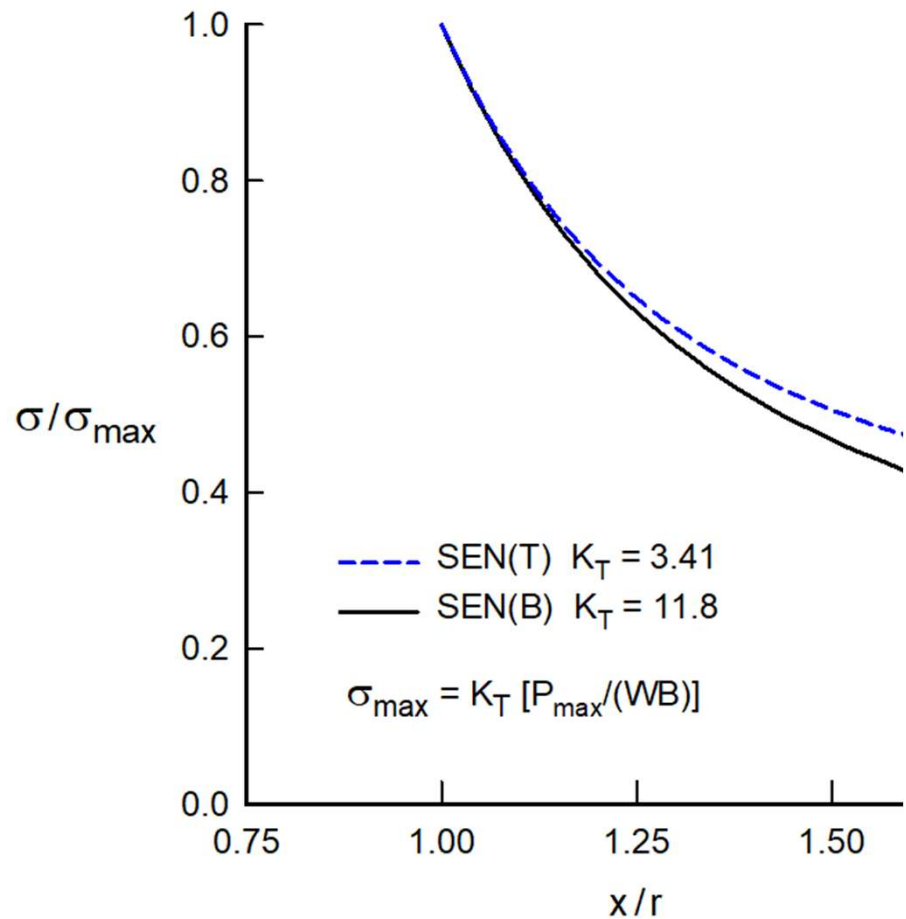
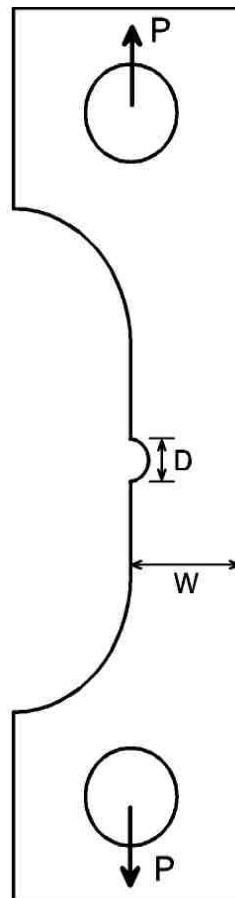
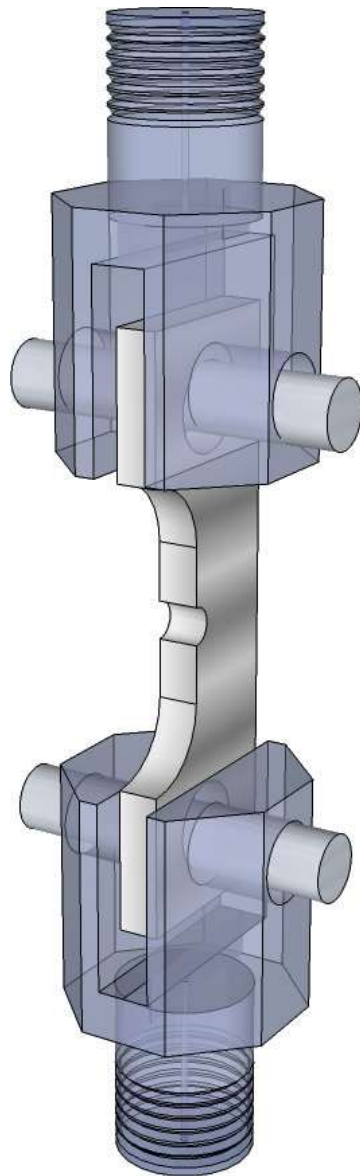
Turbistan (engine spectra)

* Loading and materials are not associated

Outline of Presentation

- *Rainflow-on-the-Fly* methodology (FASTRAN subroutine)
- Small-Crack Programs
- ***Single-edge-notch-bend*, SEN(B), fatigue specimens**

Single-Edge-Notch-Bend, SEN(B), Specimen to Demonstrate Fatigue-Life Analyses

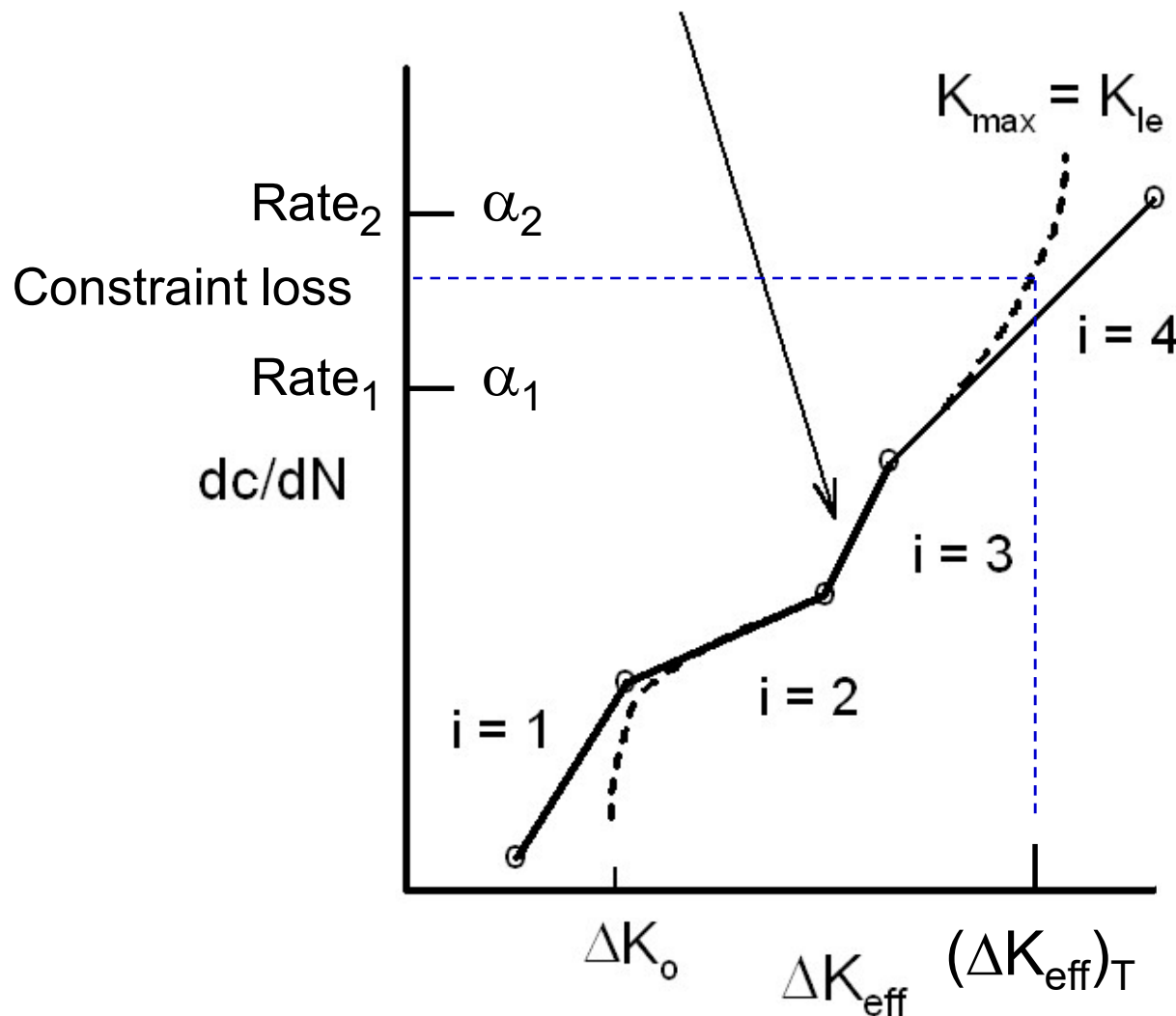


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- *Rainflow-on-the-Fly* methodology (FASTRAN subroutine)
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- ***Fatigue*** of **2024-T3** aluminum alloy notched specimens
 - o Constant-amplitude loading
 - o Aircraft spectrum loading

FASTRAN - Crack-Growth-Rate Equation

$$dc/dN = C_{1i} (\Delta K_{eff})^{C_{2i}} [1 - (\Delta K_o / \Delta K_{eff})^p] / [1 - (K_{max} / K_{le})^q]$$



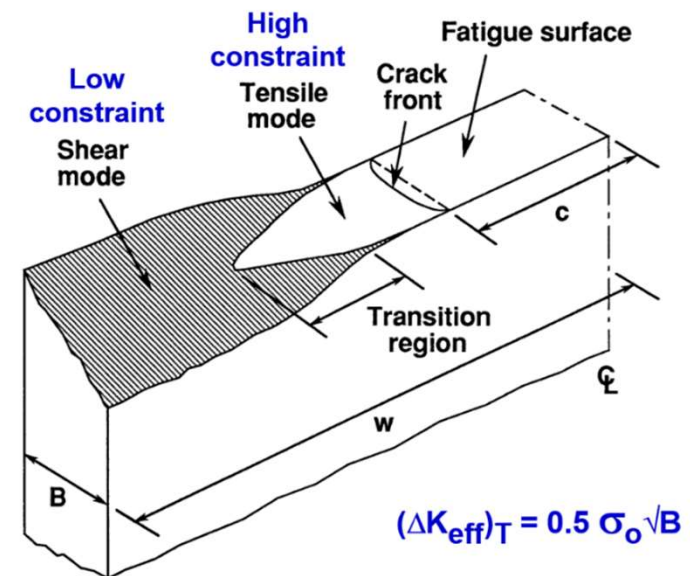
Crack-closure theory:

$$\Delta K_{eff} = U \Delta K$$

$$U = f(R, \alpha, \dots)$$

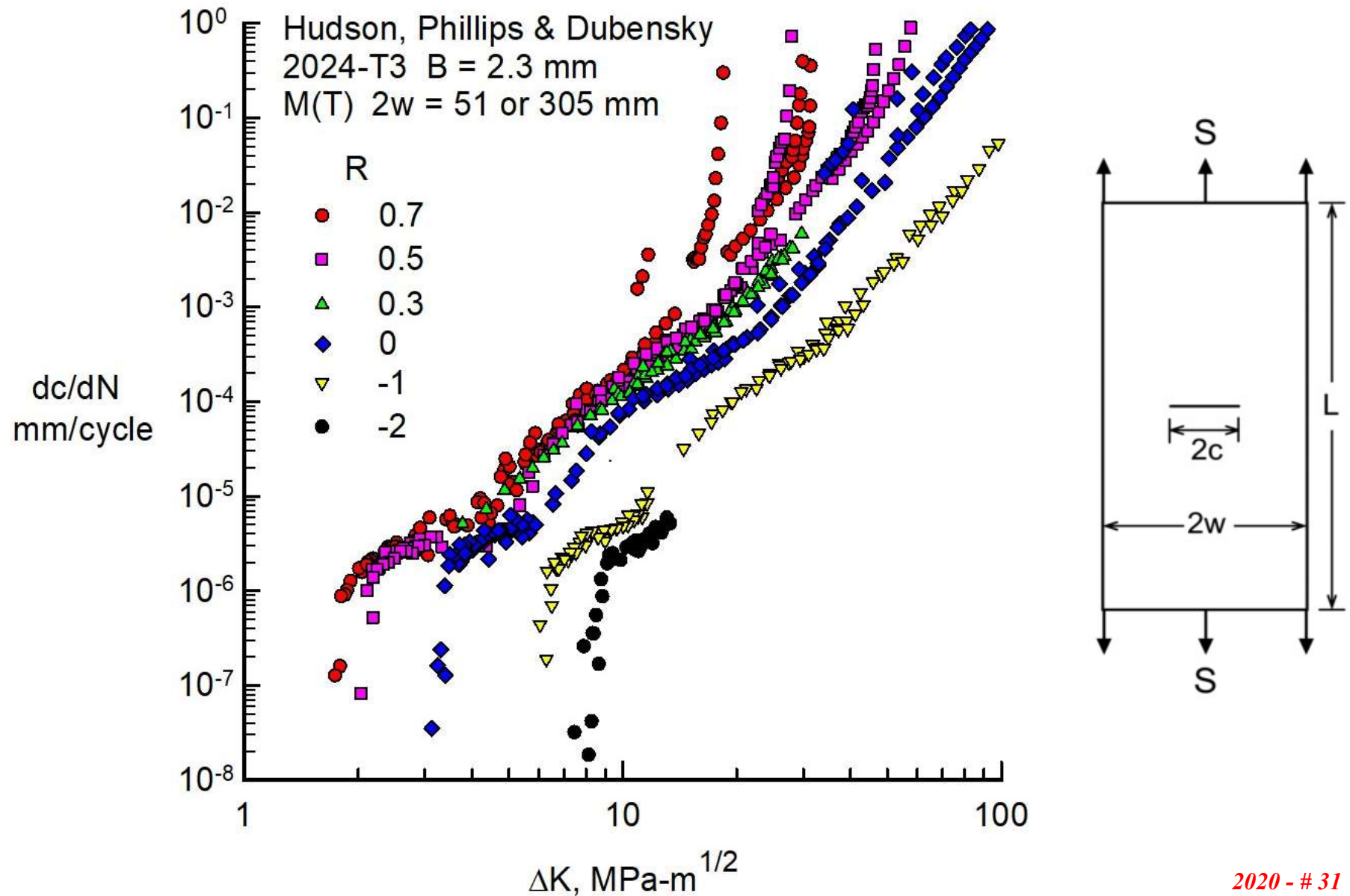
$$\Delta K_o = f(C_3, C_4, R) = 0$$

$$K_{le} = g(K_F, m)$$



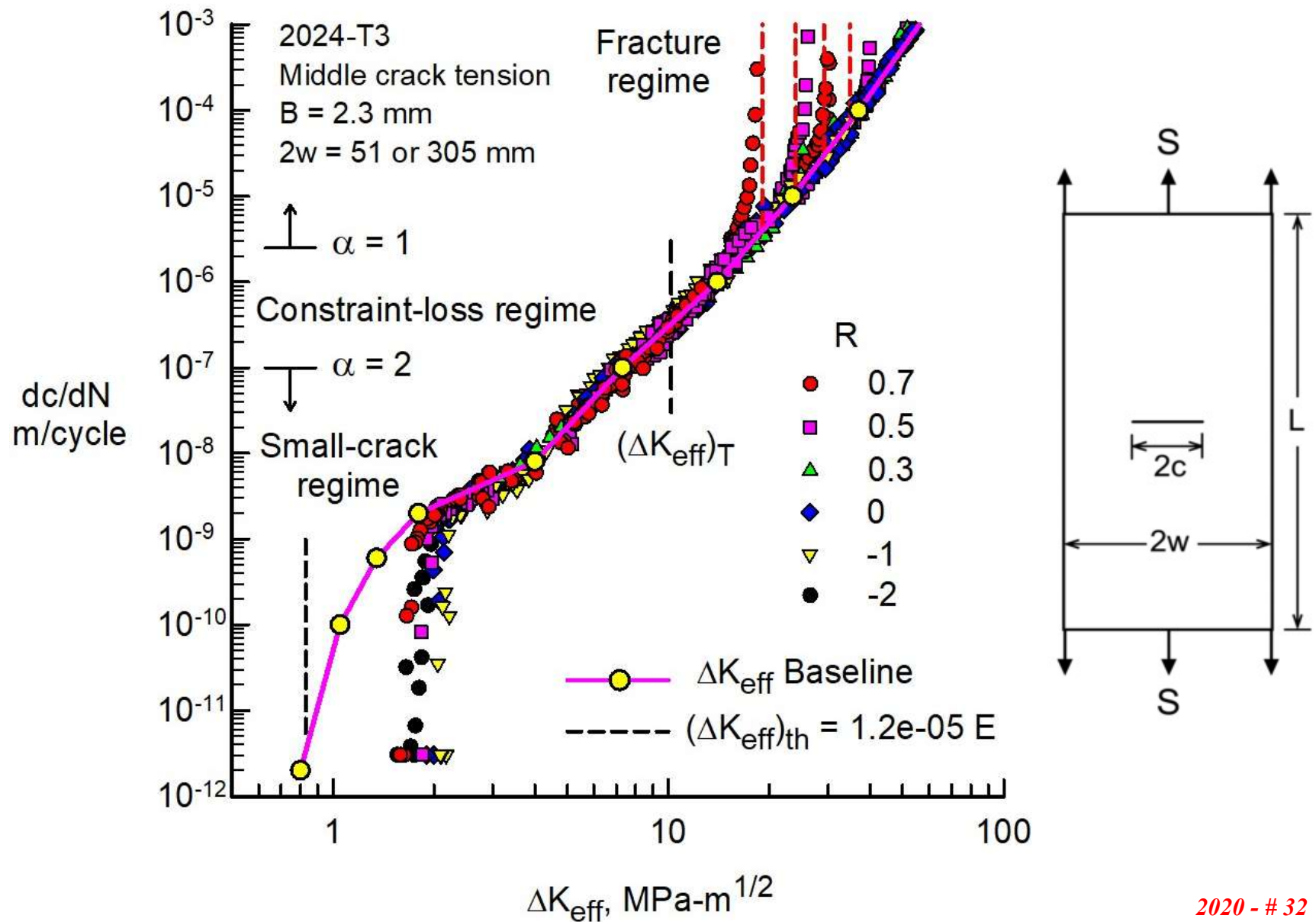
$$(\Delta K_{eff})_T = 0.5 \sigma_o \sqrt{B}$$

Stress-Intensity Factor (SIF) against Rate Data for 2024-T3 M(T) Specimens – Hudson, Phillips and Dubensky (NASA LaRC)

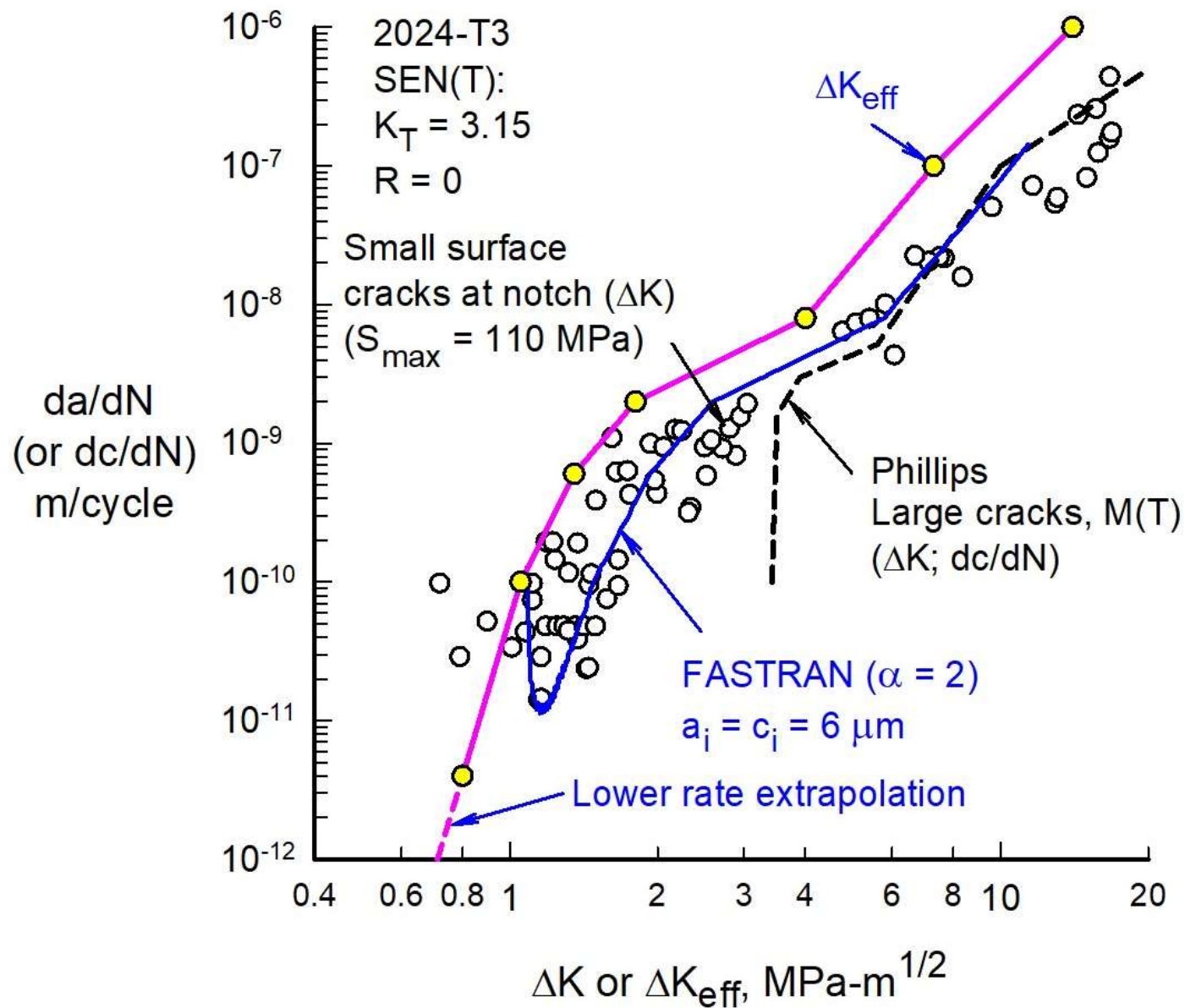


Effective SIF Relation for 2024-T3 M(T) Specimens

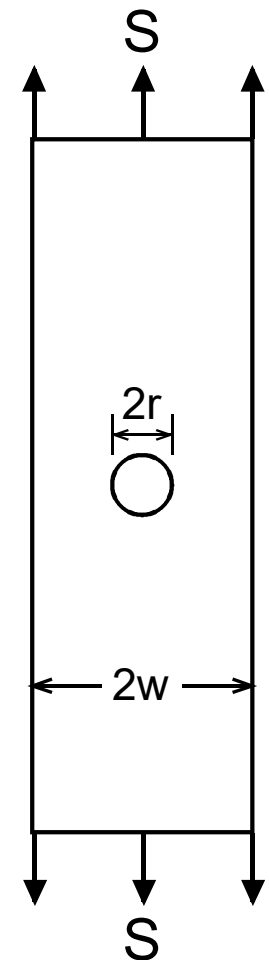
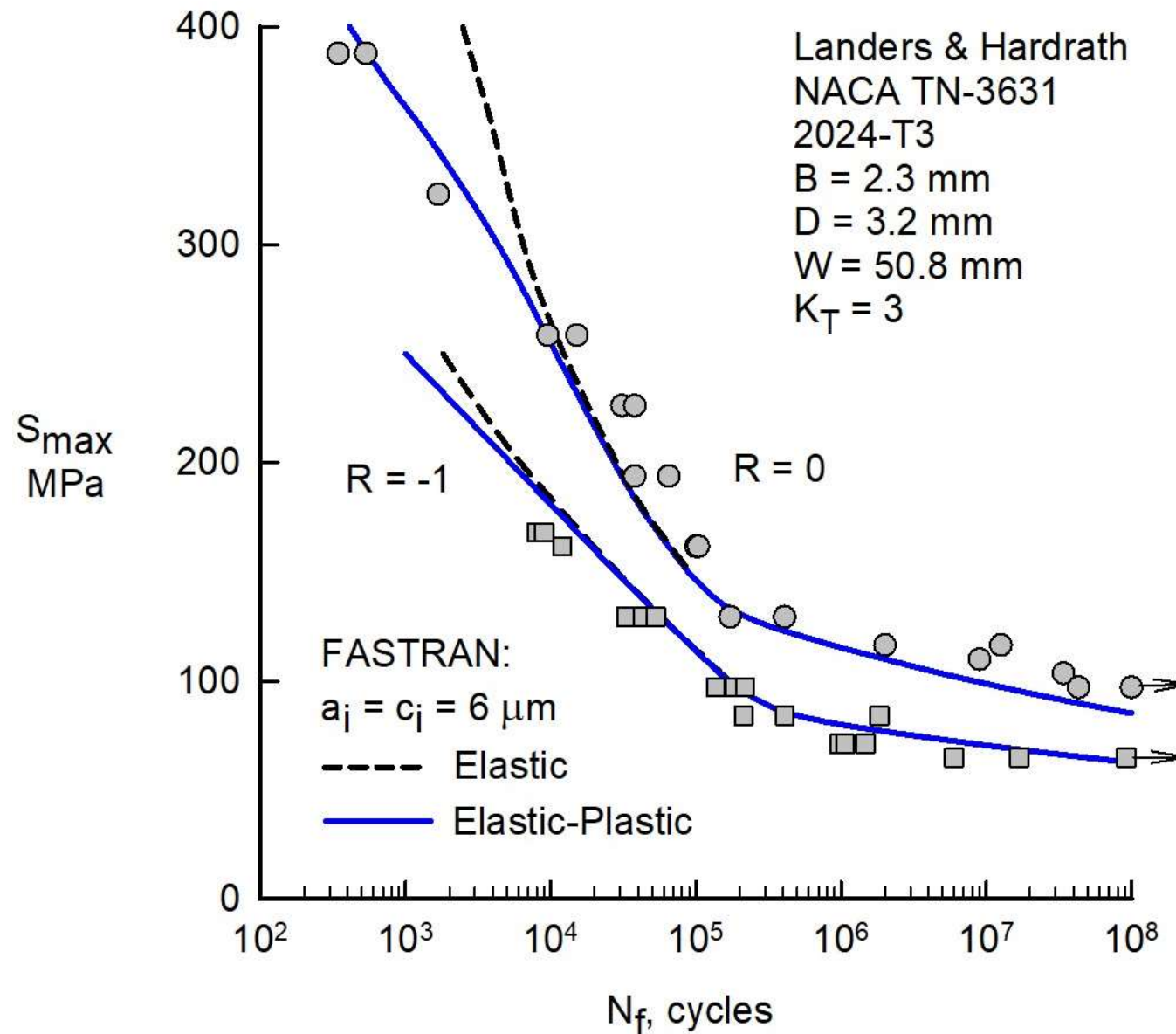
Newman, Swain and Phillips (1986)



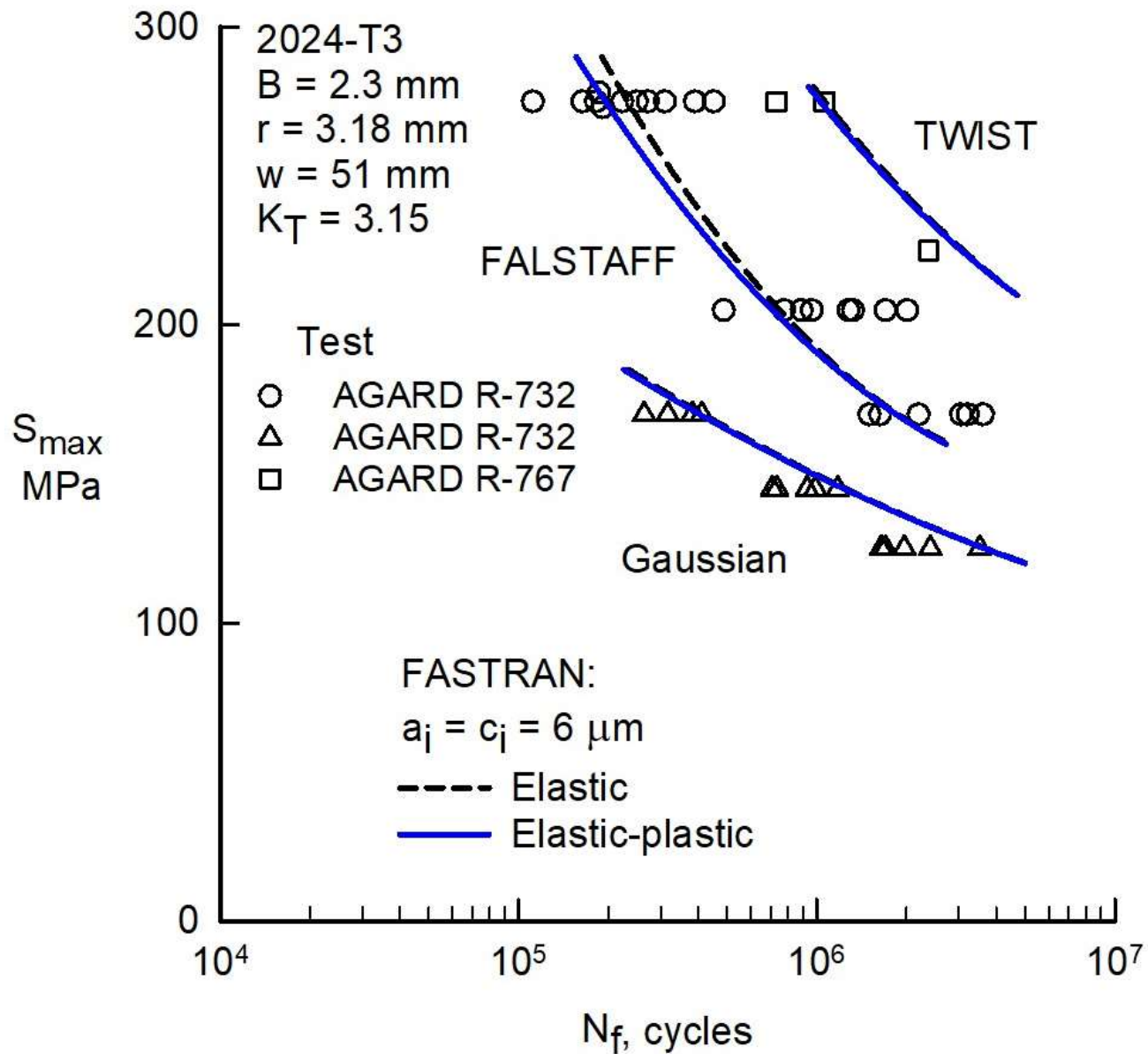
Comparison of Rate Data for Small and Large Cracks in 2024-T3 Newman, Swain and Phillips (1986)



2024-T3 – Calculated Fatigue (S-N) Behavior (R = 0 and -1)



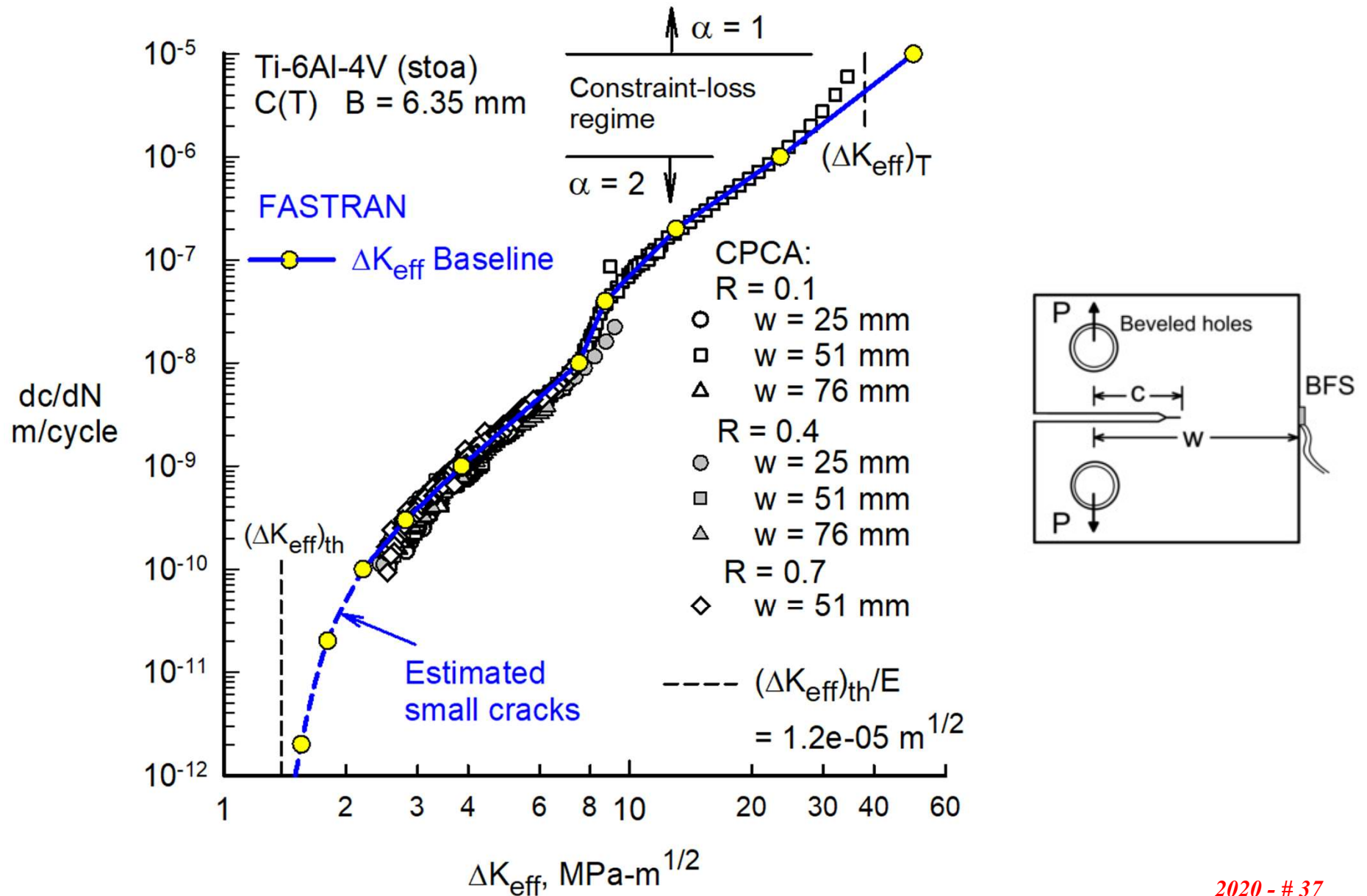
2024-T3 – Predicted Fatigue (S-N) Behavior for Various Spectra



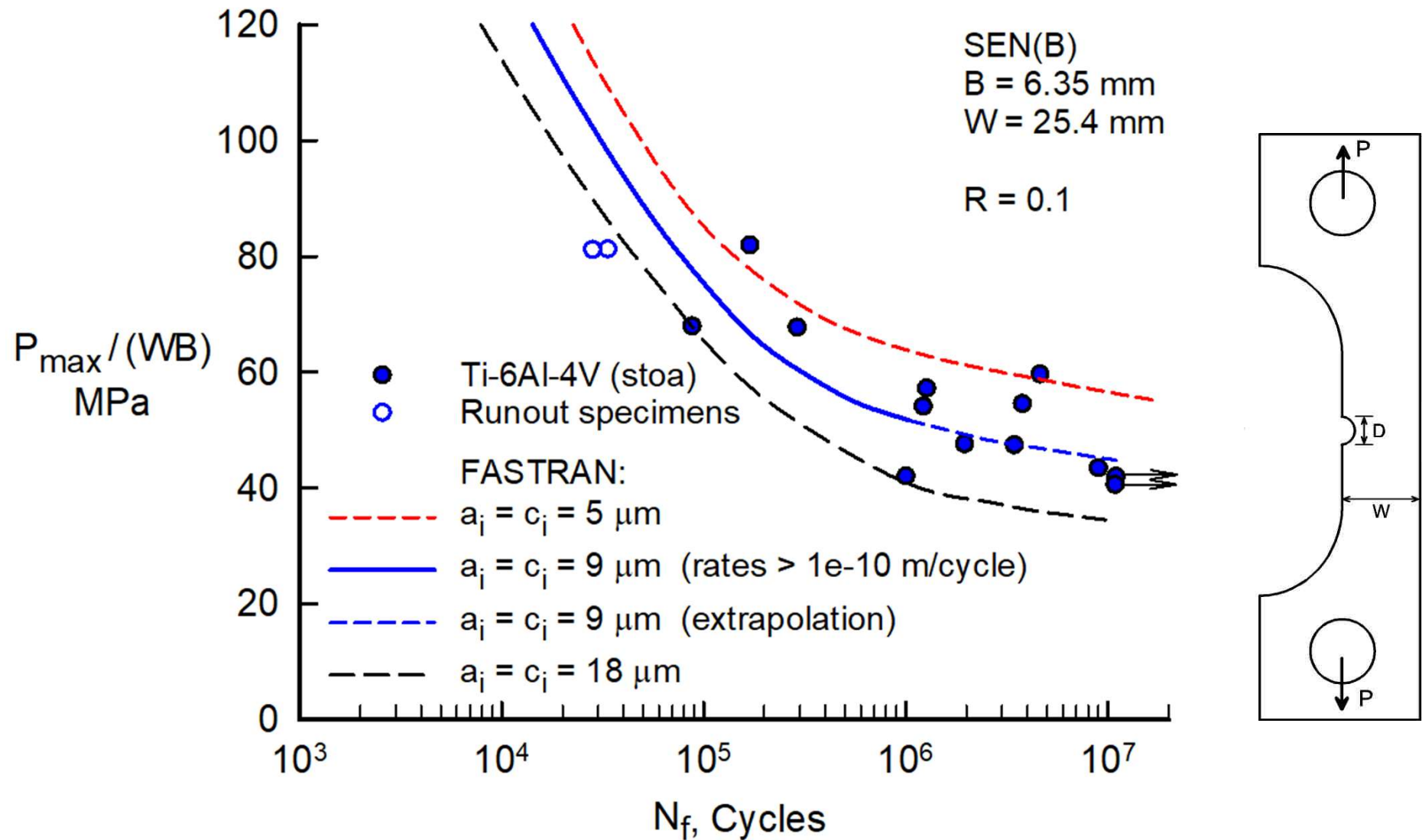
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 - Aircraft spectrum loading
- ***Fatigue* of Ti-6Al-4V titanium alloy notched specimens**
 - Constant-amplitude loading
 - Aircraft spectrum loading

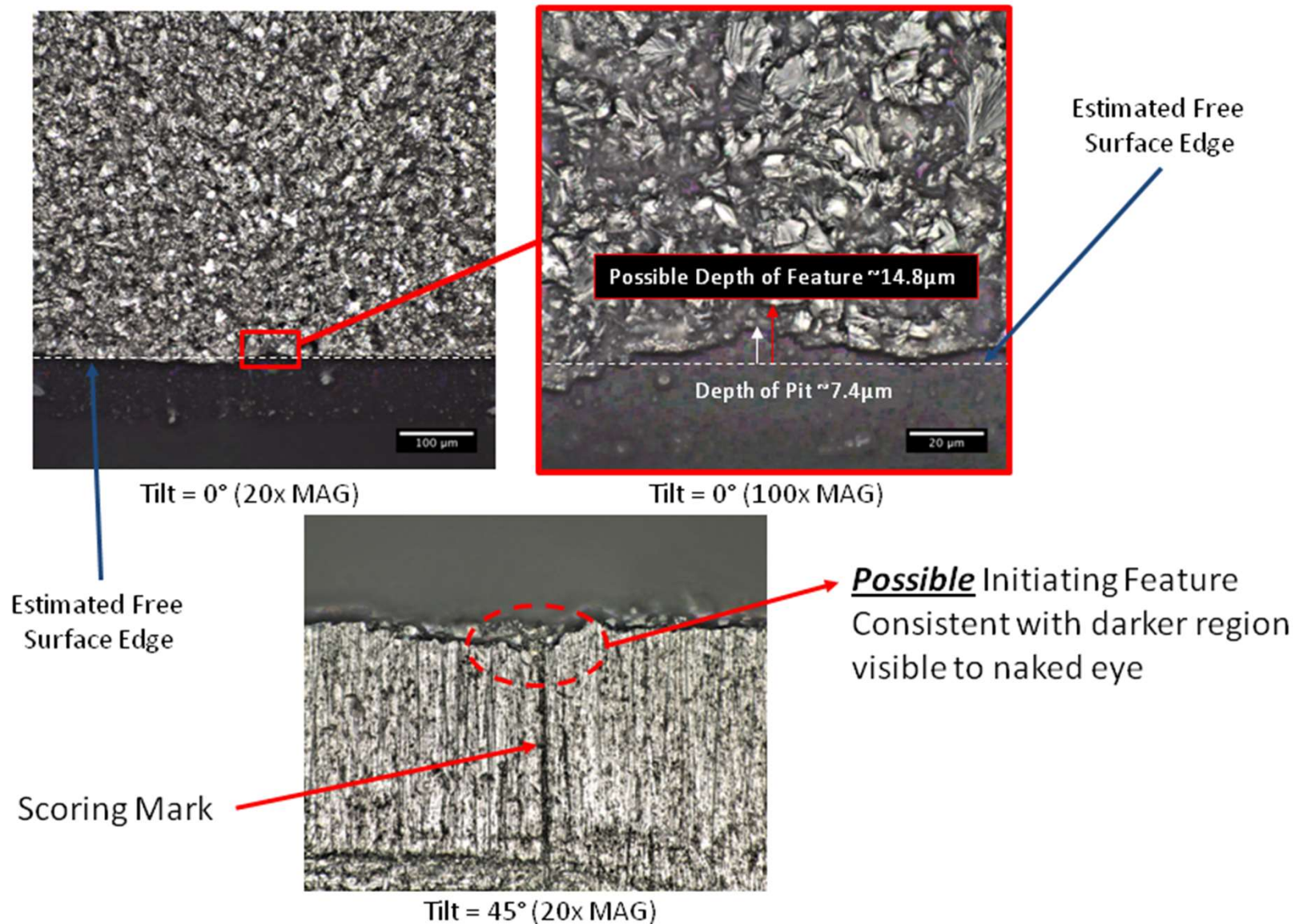
Effective SIF Relation for Ti6Al-4V (stoa) Compact Specimens Using Compression Pre-Cracking Methods (Newman et al, 2010)



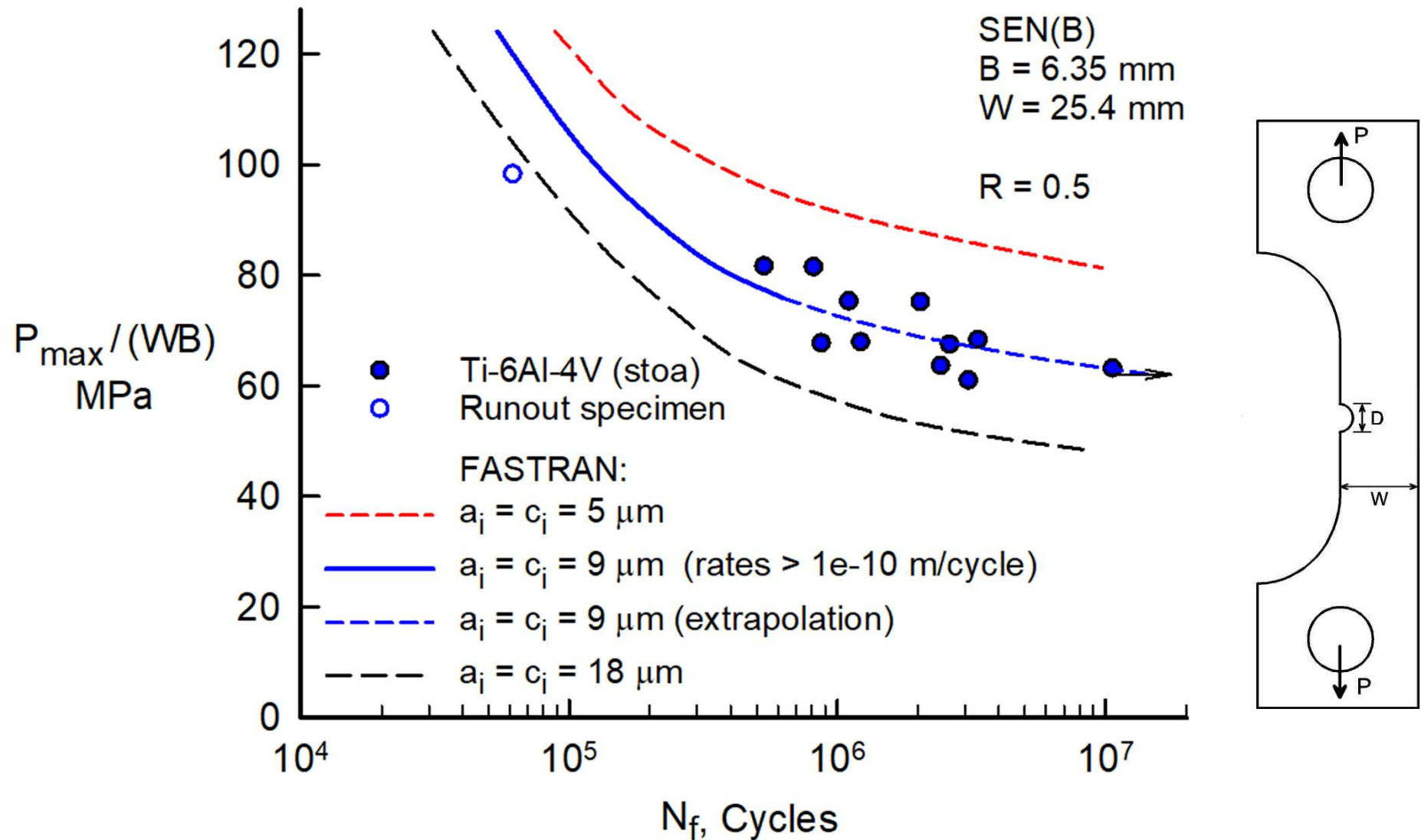
Ti-6Al-4V (stoa) – **Calculated** Fatigue (S-N) Behavior (R = 0.1)



Optical Photos of a Nucleation Site in Titanium Alloy SEN(B) (Robert Boykin, DSTO, Australia)

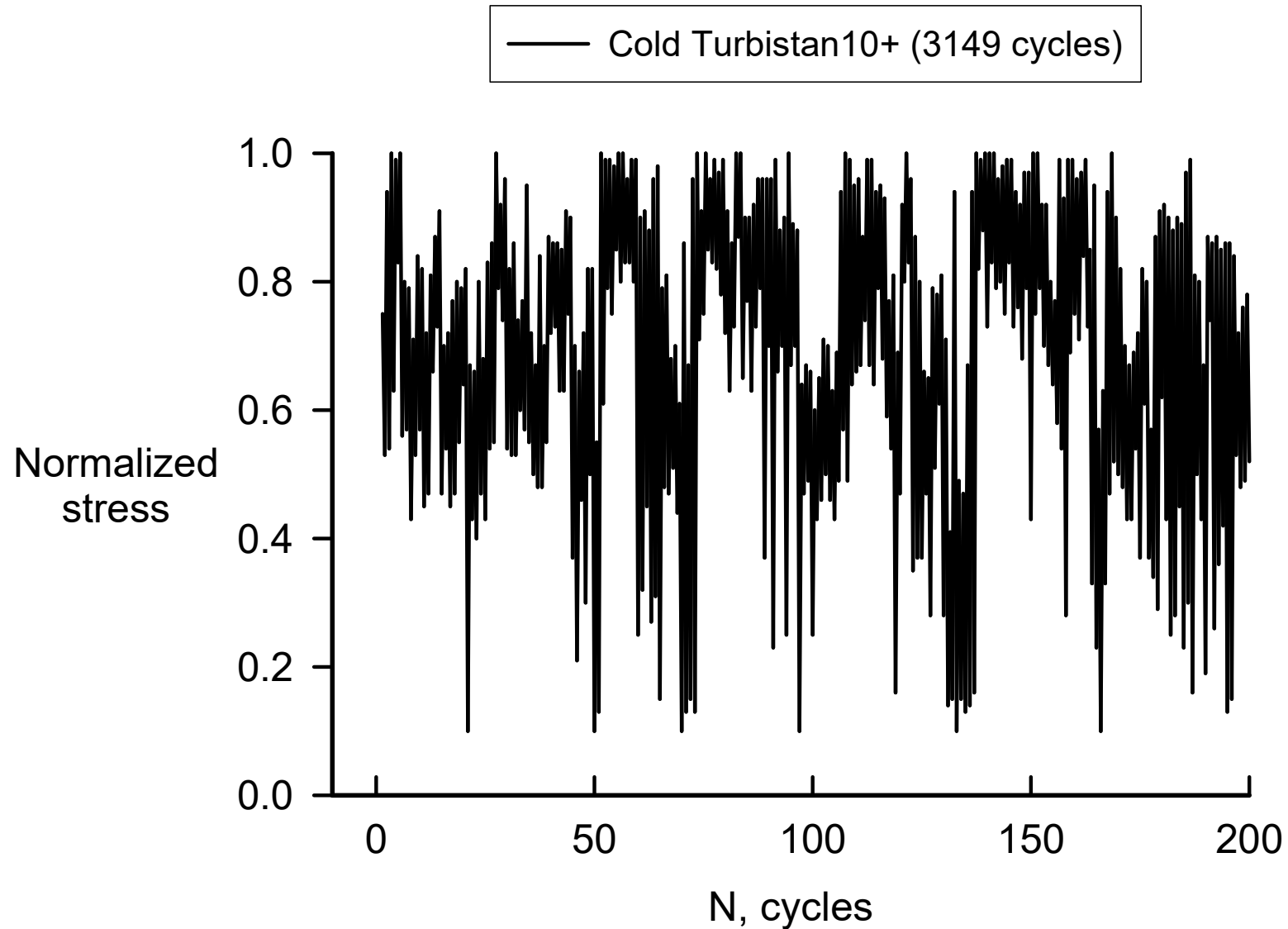


Ti-6Al-4V (stoa) – Calculated Fatigue (S-N) Behavior (R = 0.5)

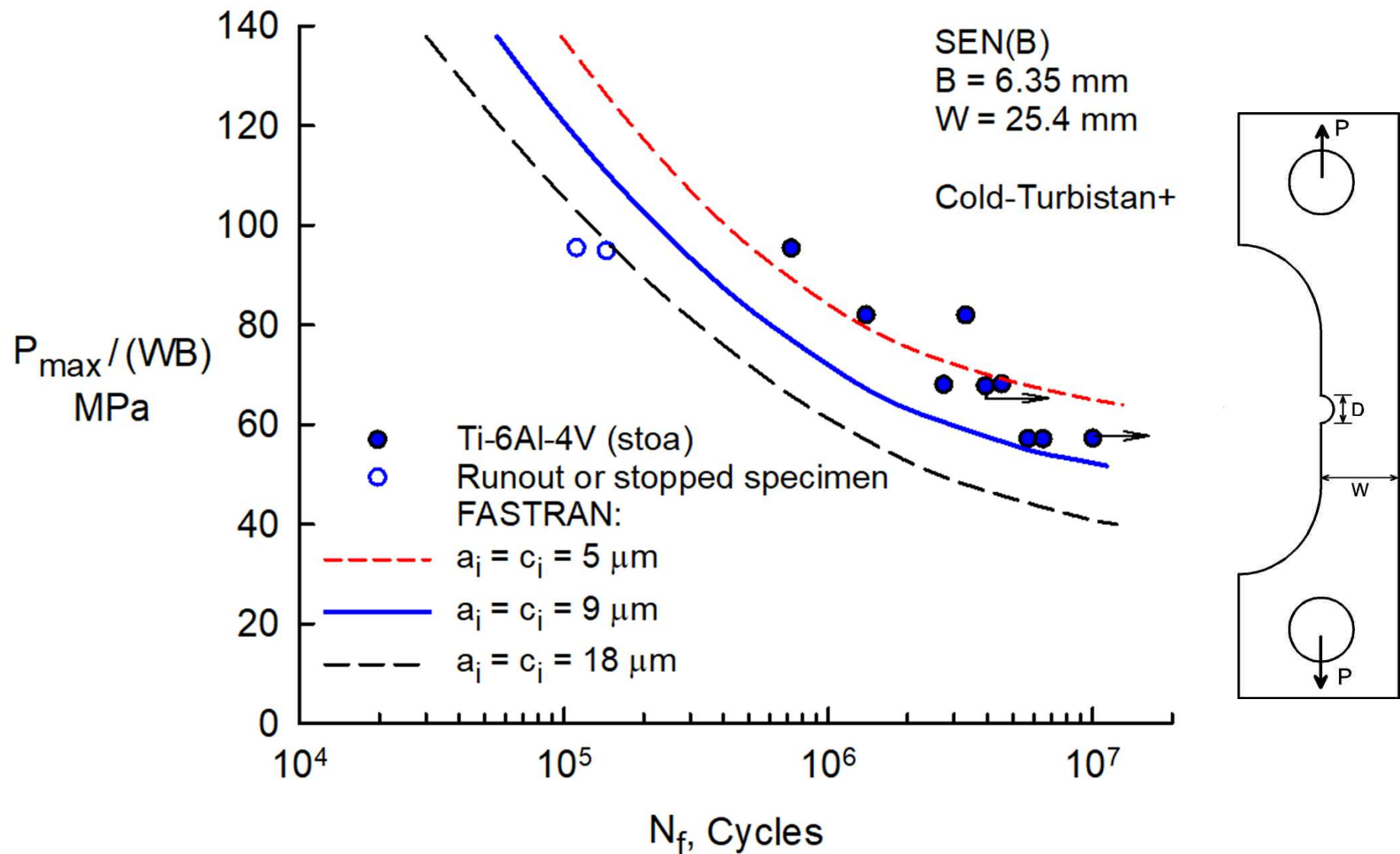


Part of Cold Turbistan10 Spectrum

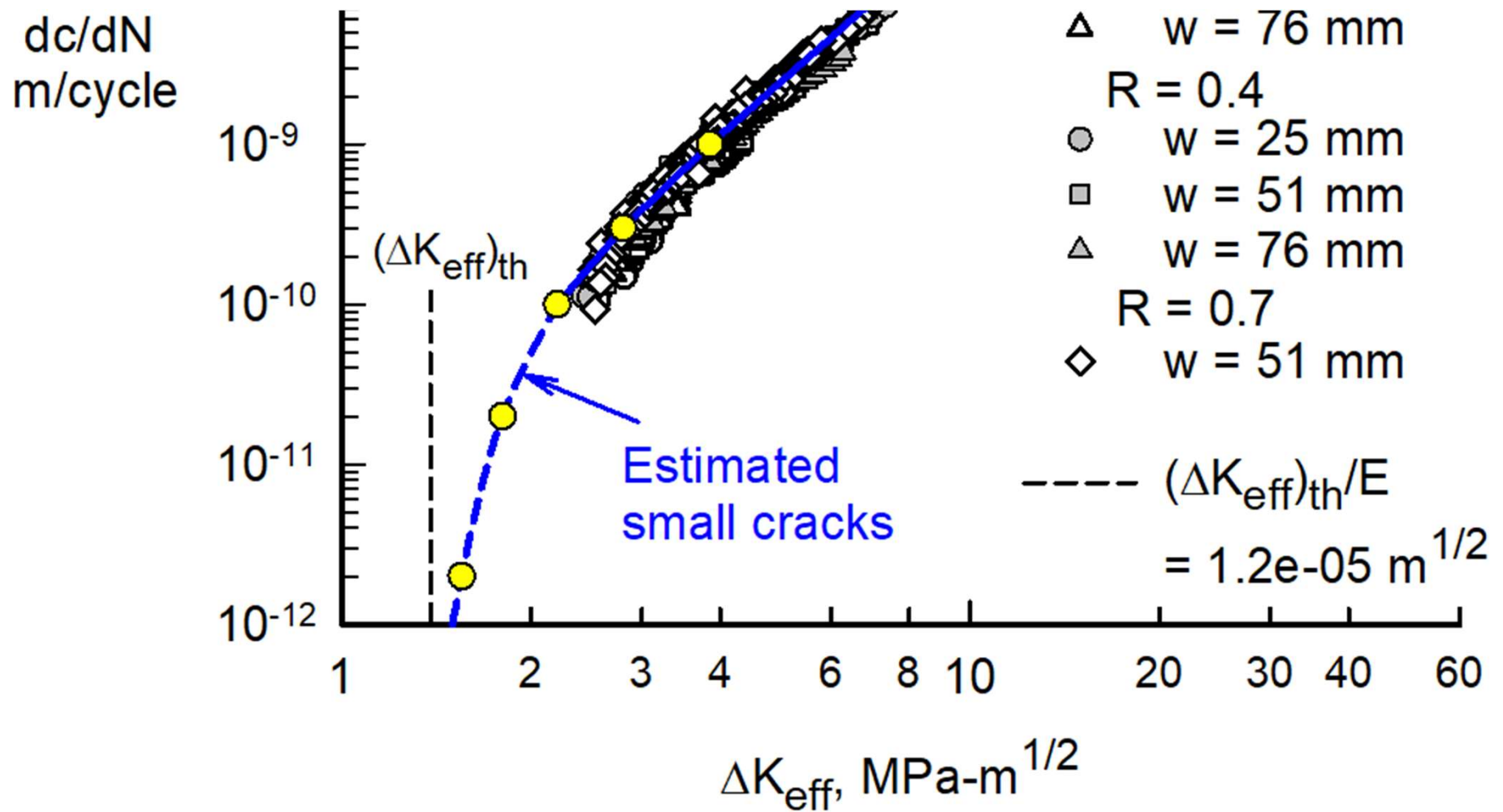
ten Have, NLR (1987)



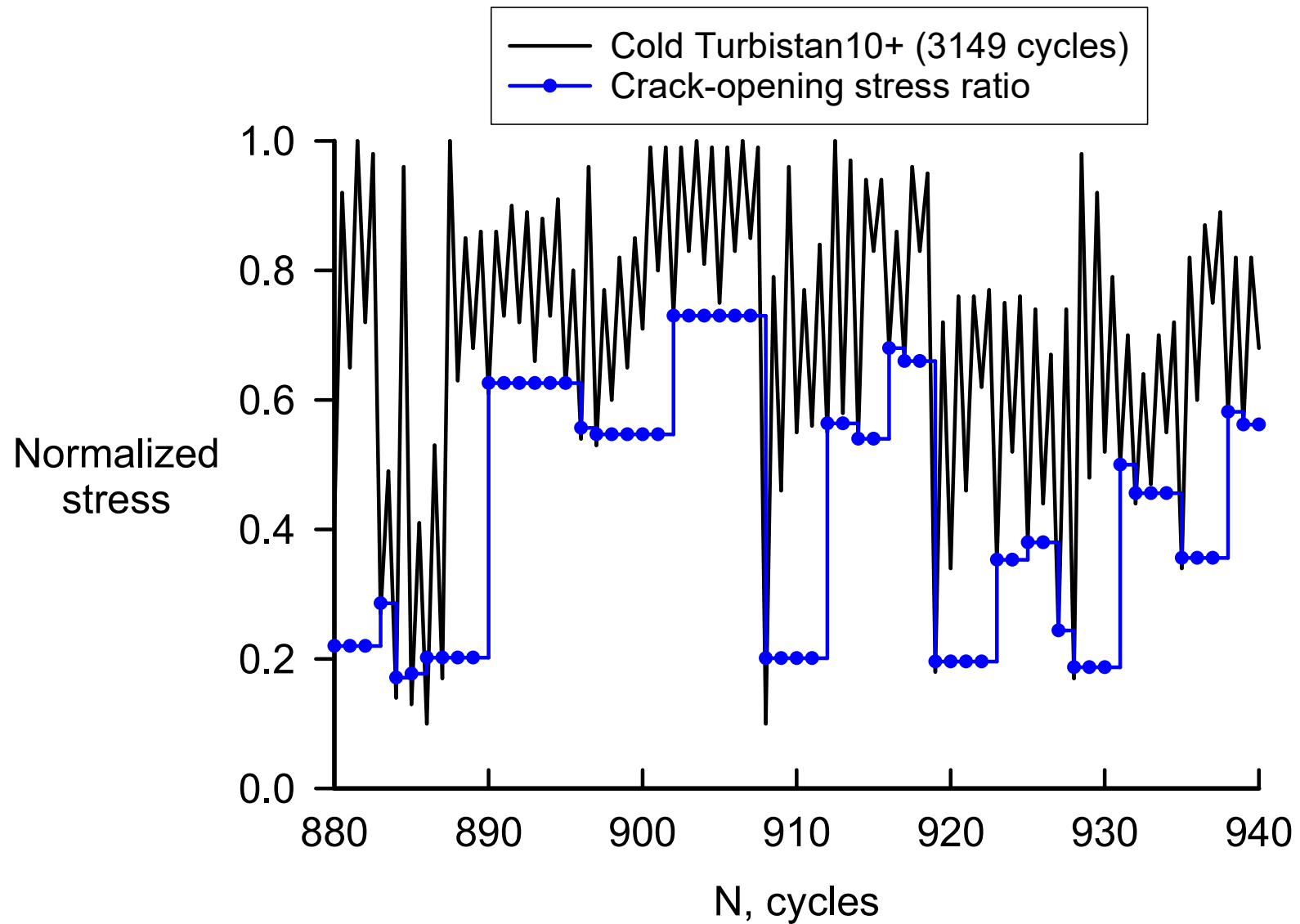
Ti-6Al-4V (stoa) – Predicted Fatigue (S-N) Behavior



Effective SIF Relation for Ti6Al-4V (stoa) Compact Specimens (2)



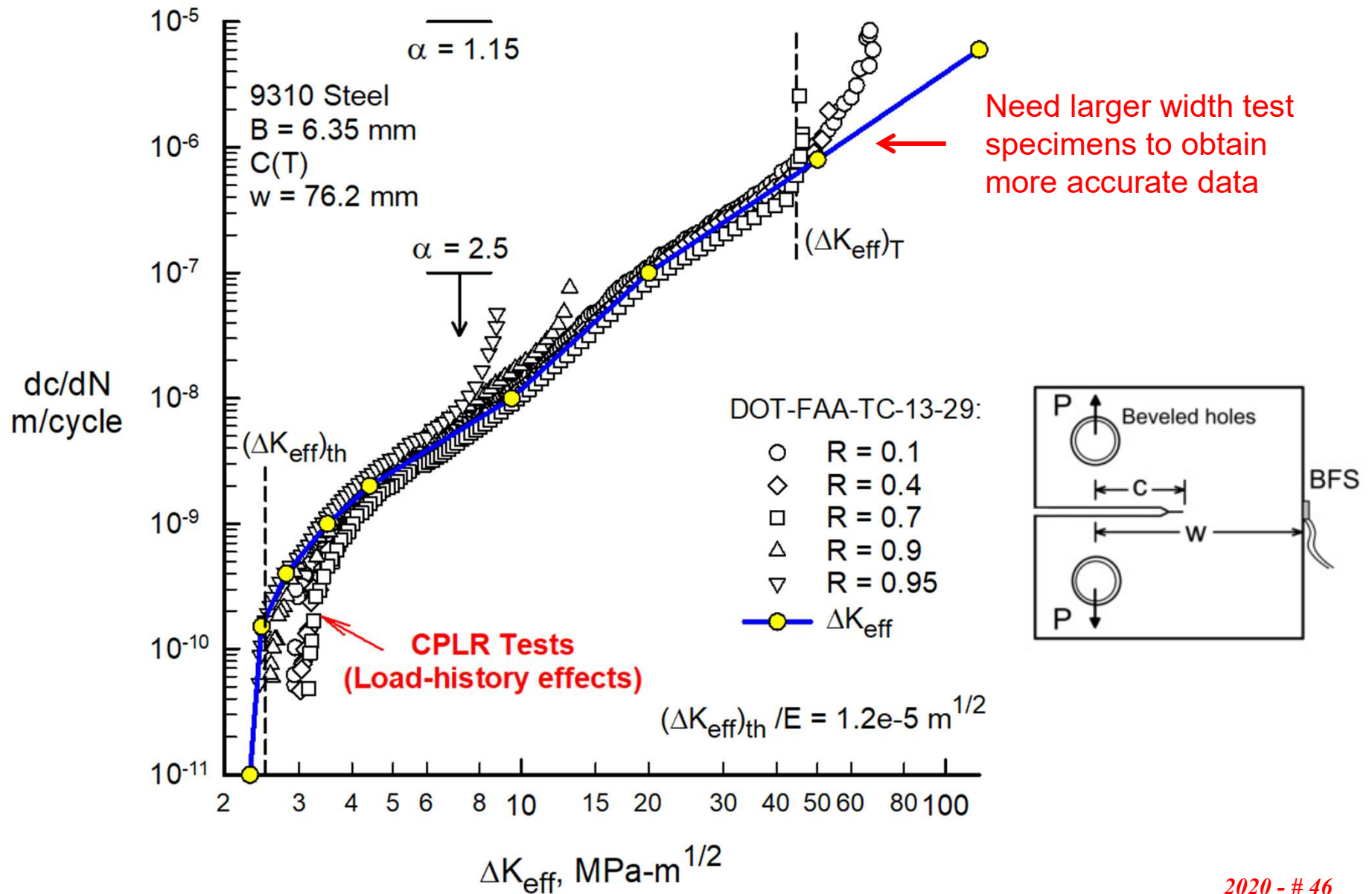
Part of Cold Turbistan10 Spectrum and Calculated Crack-Opening Stresses



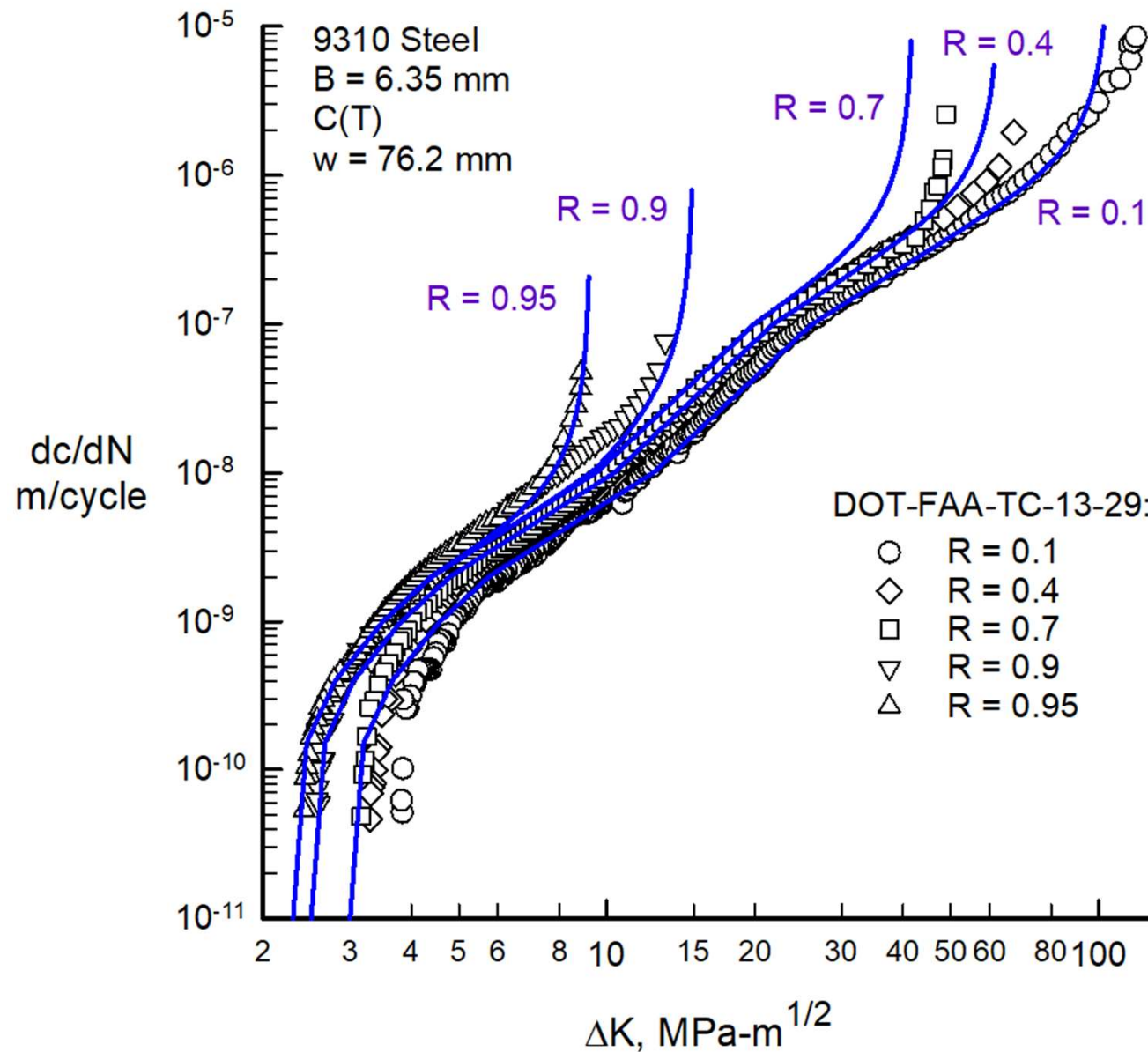
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- *Rainflow-on-the-Fly* methodology (FASTRAN subroutine)
- Small-Crack Programs
- *Single-edge-notch-bend*, SEN(B), fatigue specimens
- *Fatigue* of 2024-T3 aluminum alloy notched specimens
 - Constant-amplitude loading
 - Aircraft spectrum loading
- *Fatigue* of Ti-6Al-4V titanium alloy notched specimens
 - Constant-amplitude loading
 - Aircraft spectrum loading
- ***Fatigue* of 9310 steel notched specimens**
 - Constant-amplitude loading
 - Aircraft spectrum loading
- **Conclusions**

Effective SIF Relation for 9310 Steel Compact Specimens Using Compression Pre-Cracking Methods (Newman et al, 2014)

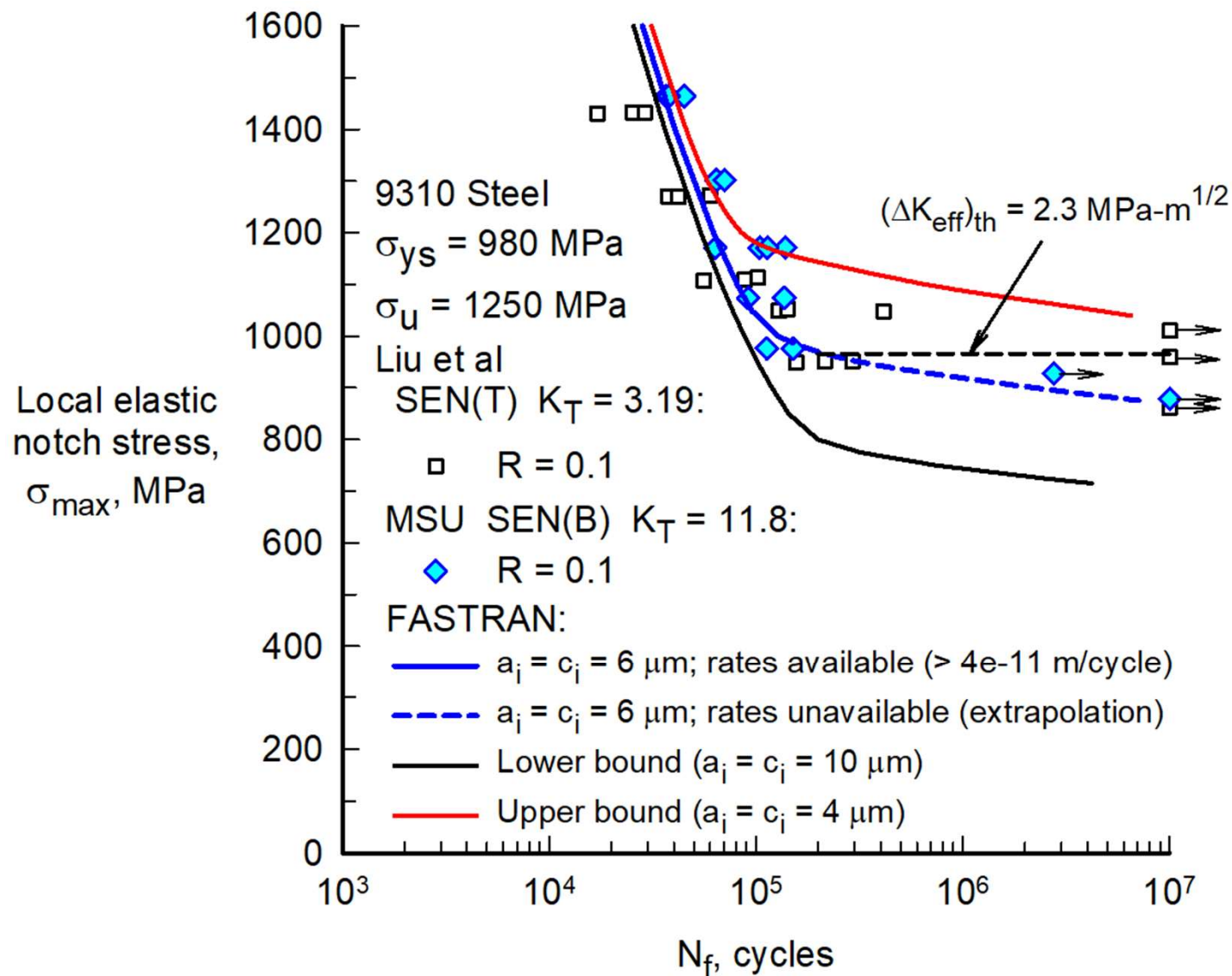


SIF against Rate Data for 9310 Steel Compact Specimens



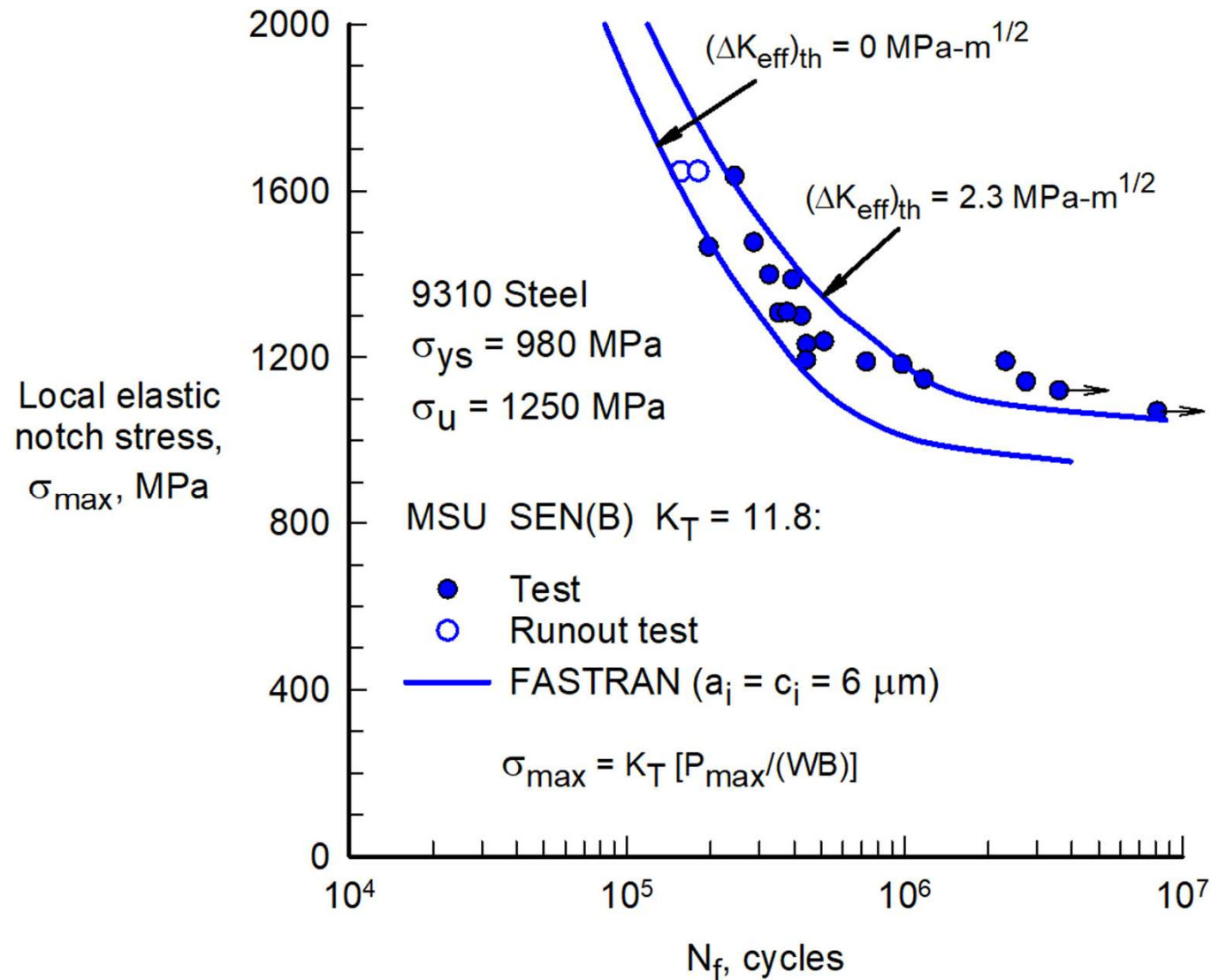
9310 Steel – Calculated Fatigue (S-N) Behavior

Constant-amplitude loading ($R = 0.1$)

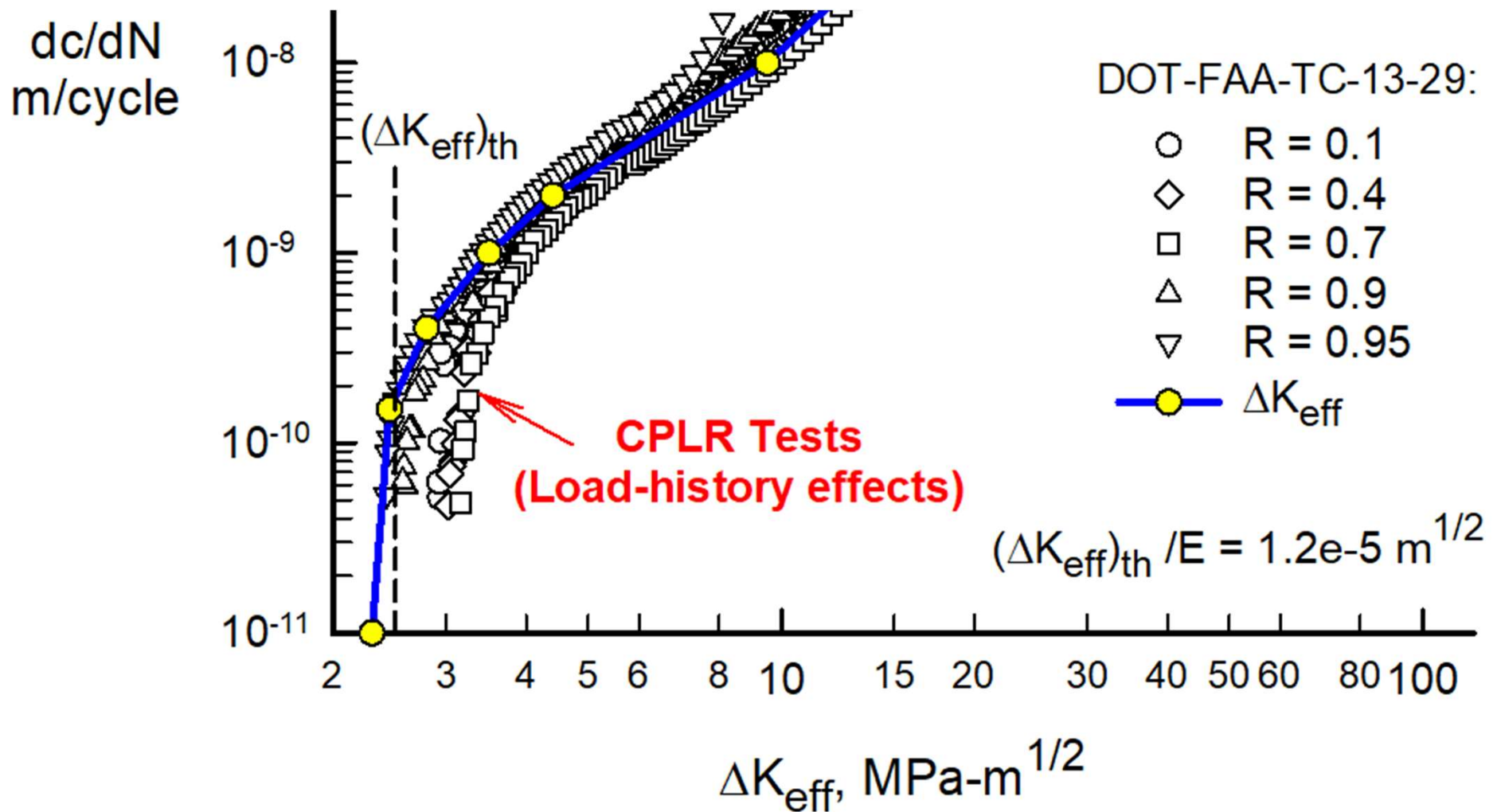


9310 Steel – Predicted Fatigue (S-N) Behavior

Spectrum loading (Cold-Turbistan+)



Effective SIF Relation for 9310 Steel Compact Specimens (2)



Conclusions

1. Constant-amplitude fatigue-crack-growth-rate data on **2024-T3** aluminum alloy, **Ti-6Al-4V (stoa)** titanium alloy, and **9310** steel specimens **correlated well** using the **crack-closure model** and **multi-linear crack-growth-rate equation**.
2. The **fatigue calculations** on **2024-T3** notched specimens **agreed well** under constant-amplitude loading using a **6- μm initial flaw size**, and **life predictions** were **very good** under Falstaff, TWIST and Gaussian spectra.
3. The **fatigue calculations** on **Ti-6Al-4V (stoa)** notched specimens **agreed well** under constant-amplitude loading using a **9- μm initial flaw size**, and **life predictions** were **conservative** under the Cold Turbistan+ spectrum **but need data for rates $< 1\text{e-}10$ m/cycle**.
4. The **fatigue calculations** on **9310 steel** notched specimens **agreed well** under constant-amplitude loading using a **6- μm initial flaw size**, and **life predictions** were **slightly conservative** under the Cold Turbistan+ spectrum.

***Fatigue of Engineered Metallic Materials
is Crack Propagation***

Thank You, Very Much!

Questions?