FASTRAN
AN ADVANCED NON-LINEAR CRACK-CLOSURE BASED LIFE-PREDICTION CODE

J. C. Newman, Jr.

Department of Aerospace Engineering

Mississippi State University

AFGROW WORKSHOP
Layton, Utah
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Mississippi State
UNIVERSITY

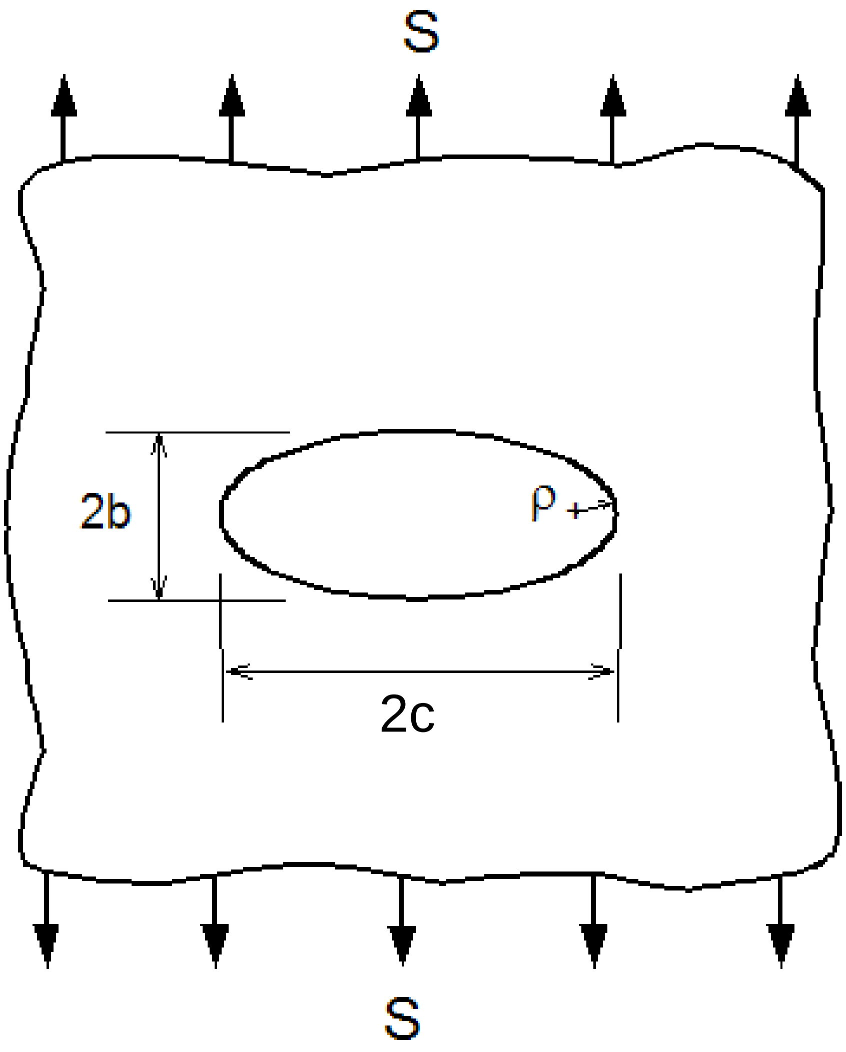
ffa

OUTLINE OF PRESENTATION

- **Brief History on Fatigue-Crack Growth**
- **Plasticity-Induced Crack-Closure Model**
- **Crack Initiation and Small-Crack Behavior**
- **Fatigue-Crack Growth and Fracture**
- **Concluding Remarks**

Stress Concentration Factor for an Elliptical Hole in an Infinite Plate

Inglis (1913)



$$K_T = 1 + 2\sqrt{\mathbf{c} / \rho}$$

$$\sigma_e = S\, K_T$$

$$\sigma_e = S + 2\, S \sqrt{\mathbf{c} / \rho}$$

Notch Strength Analysis – Fracture Mechanics

$$K_T = 1 + 2\sqrt{c/\rho}$$

$$\sigma_e = S + 2S\sqrt{c/\rho}$$

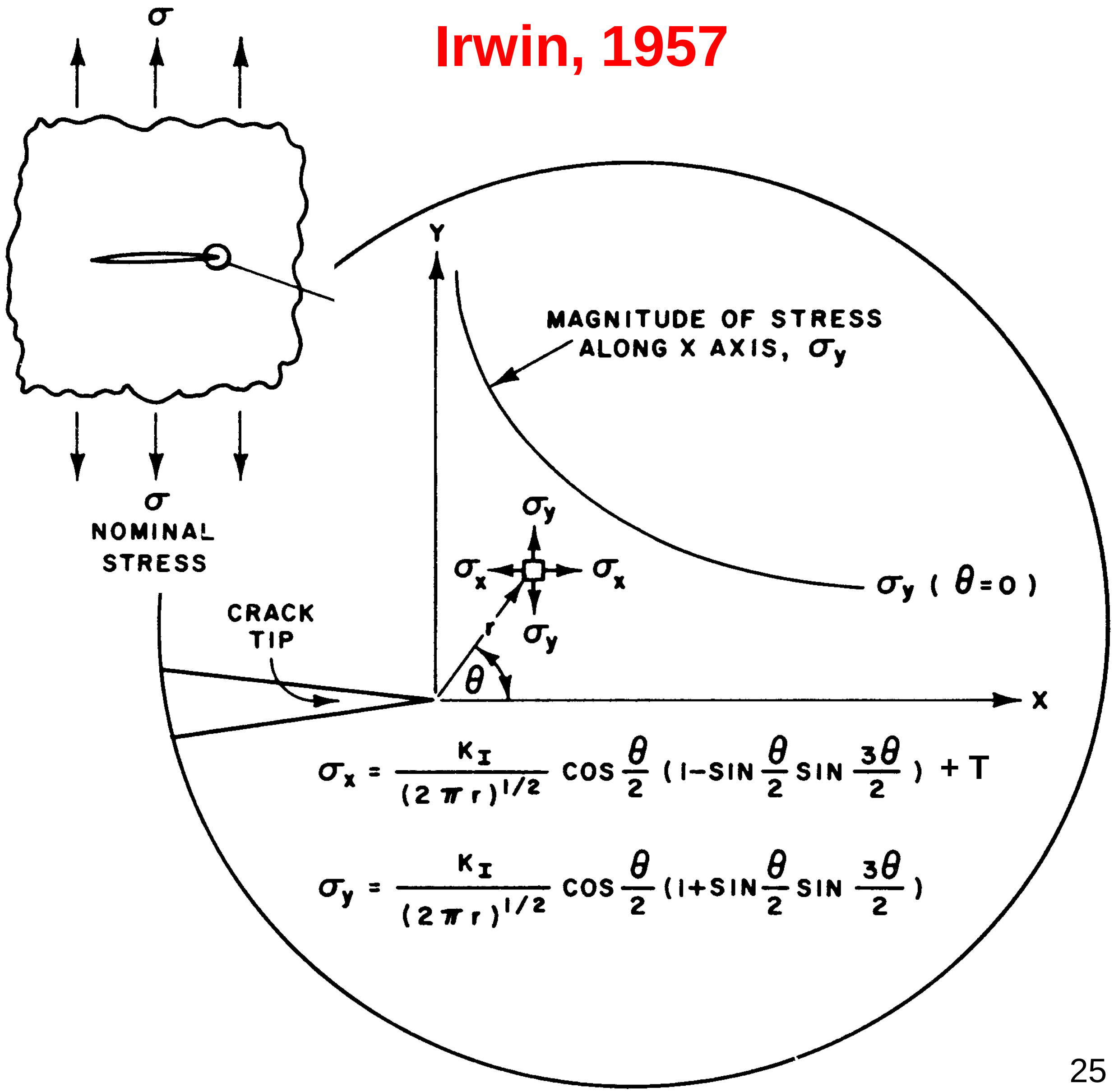
Paul Kuhn
Notch Strength Analysis
(Neuber)

George Irwin
Fracture Mechanics
(Griffith)

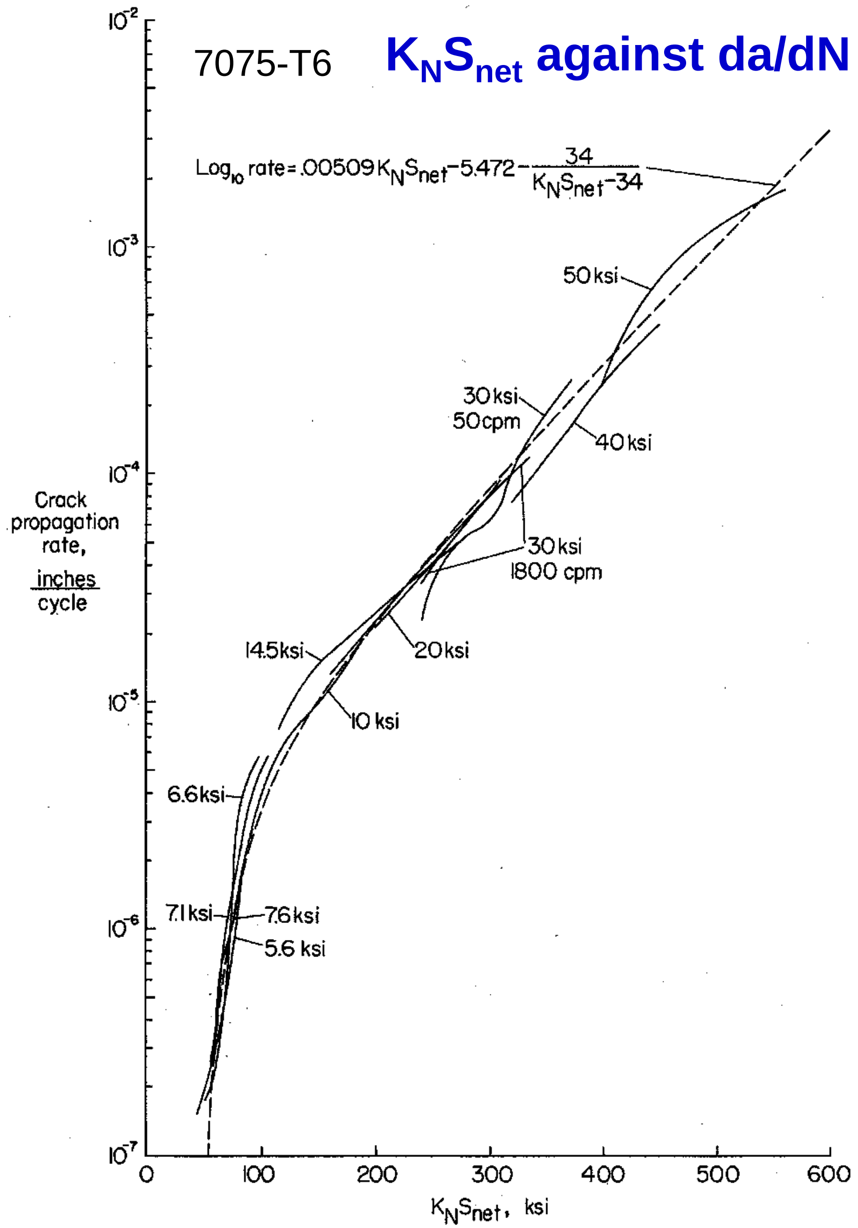
Father of "Modern" Fracture Mechanics

George Rankin Irwin
(1907-1998)

Irwin, 1957

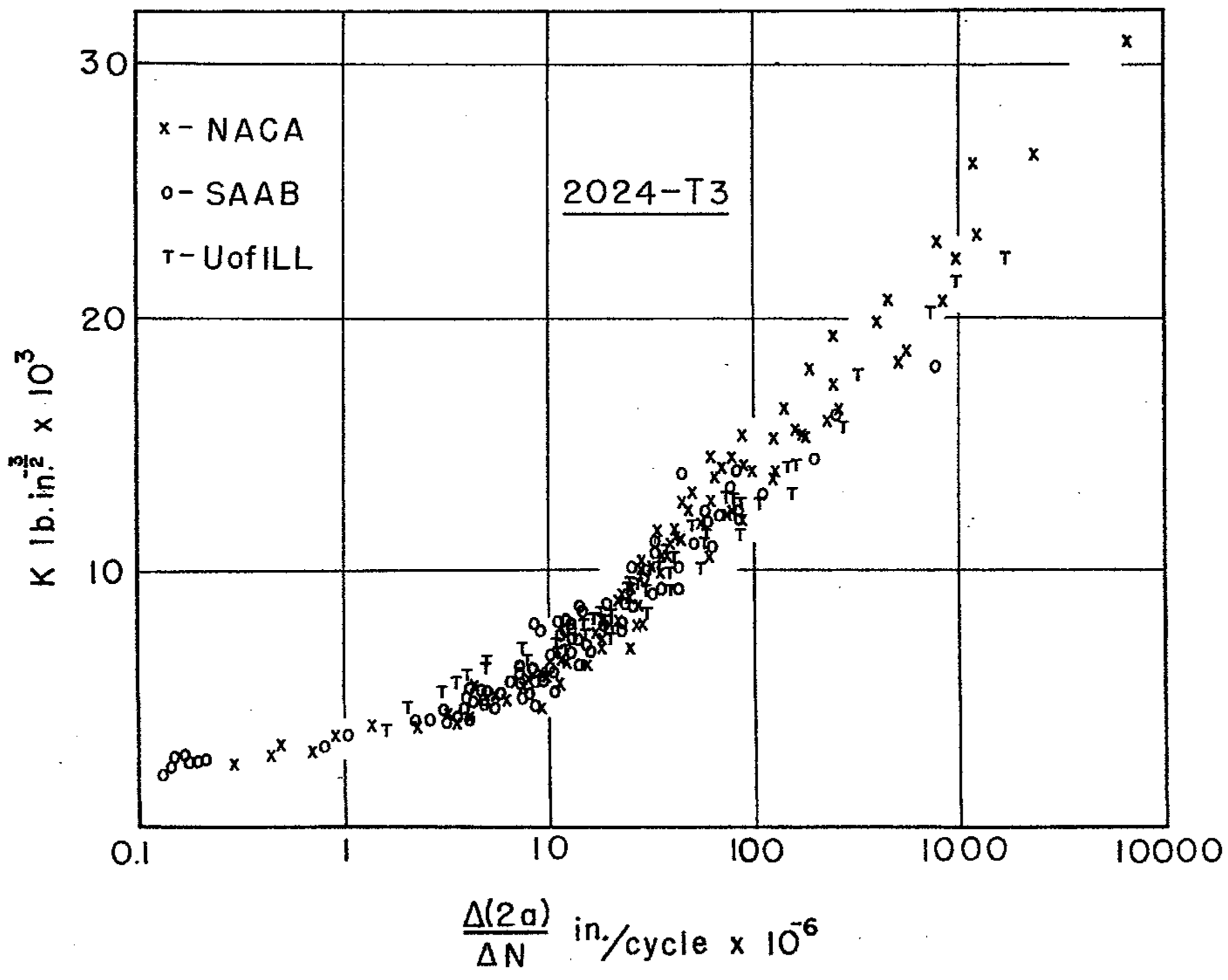


Notch-Strength Analyses: McEvily and Illg (LaRC), NACA TN-4394, 1958



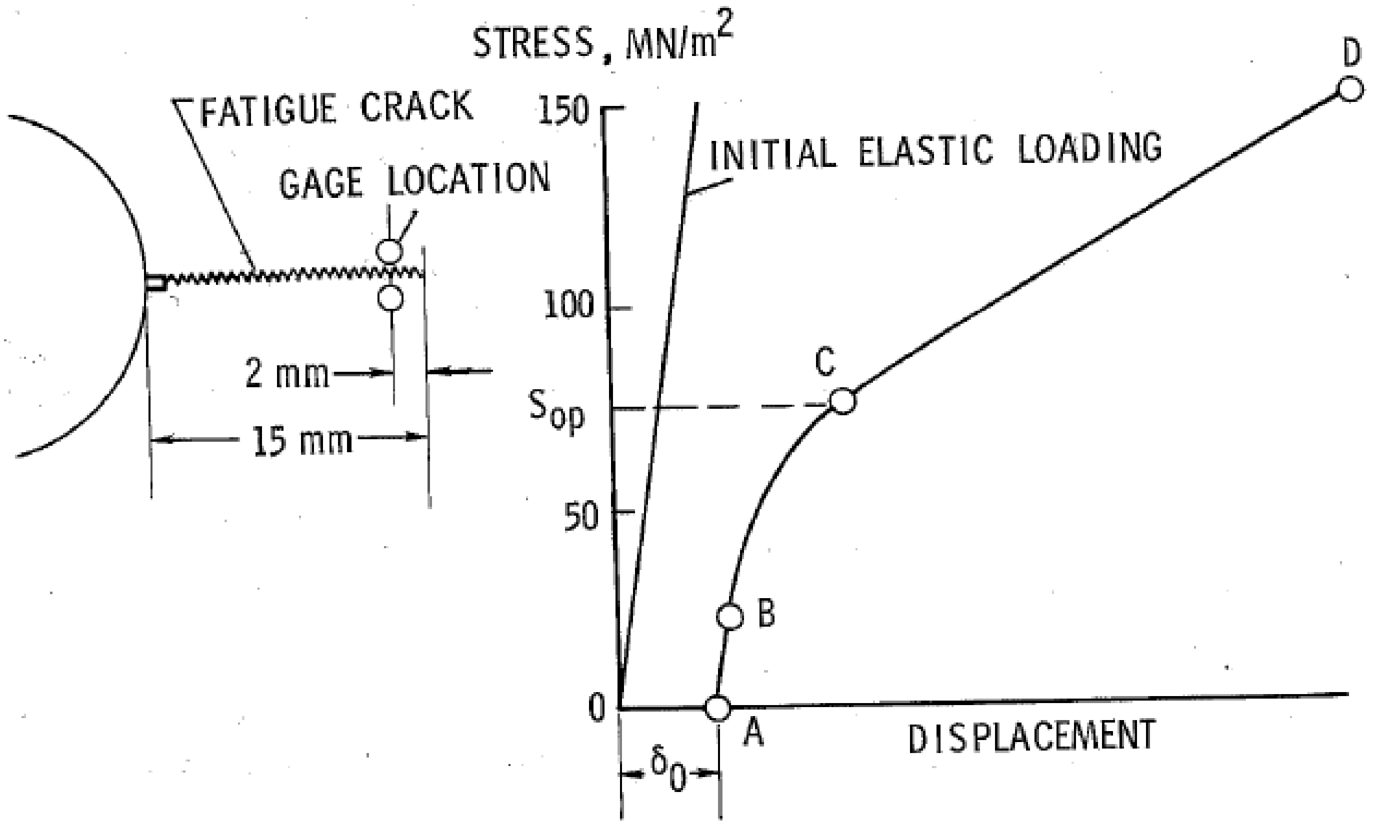
Fracture Mechanics: Paris, Gomez, and Anderson, Trends in Engineering, Seattle, WA, 1961

LEFM: K against d(2a)/dN



Paris (1970):
$K_N S_{net} \sim K_{max}$

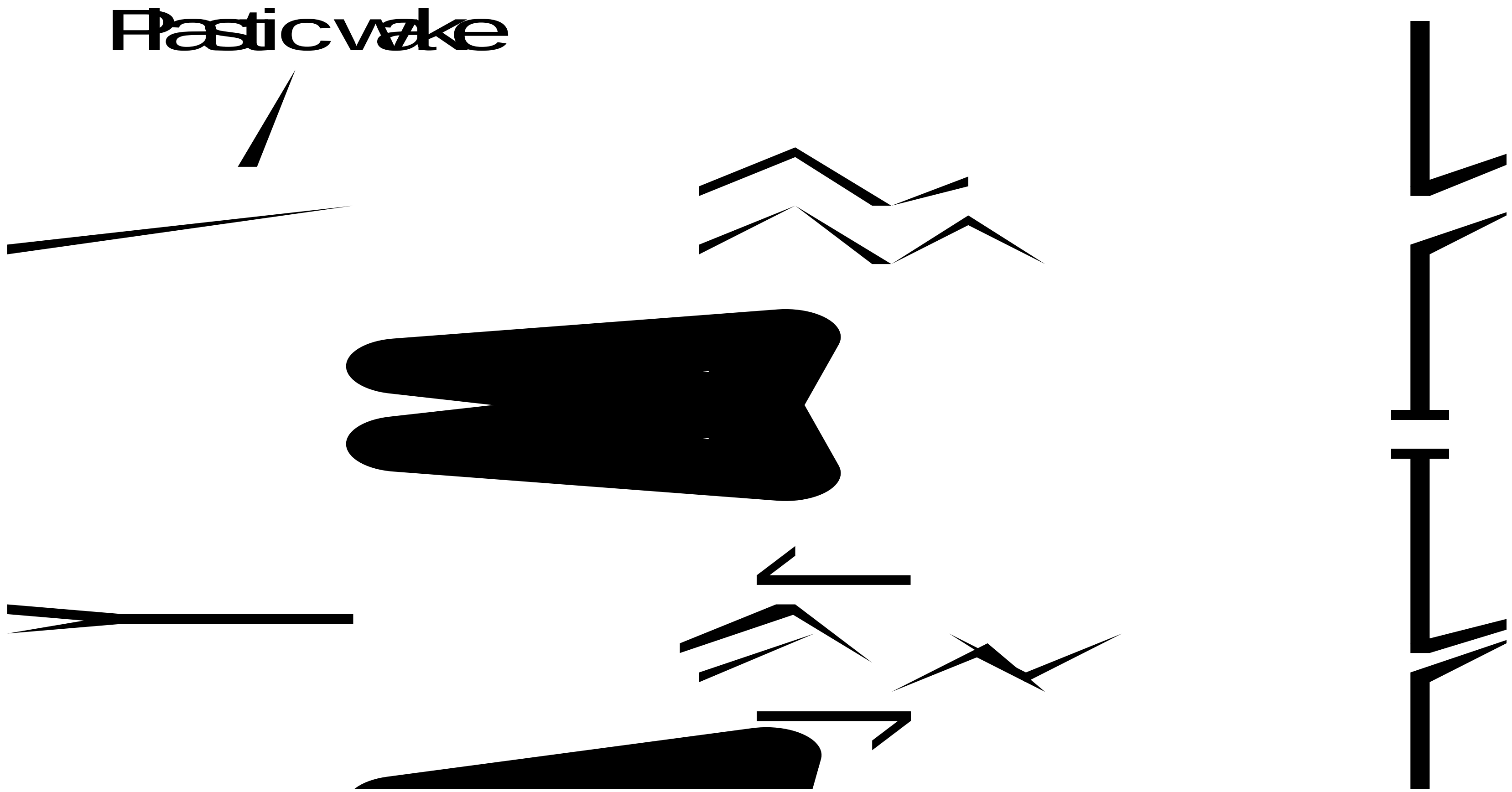
Plasticity-Induced Fatigue-Crack Closure: Elber, 1968



(a) CRACK CONFIGURATION AND GAGE LOCATION

(b) APPLIED STRESS - DISPLACEMENT RELATION

DOMINANT MECHANISMS OF FATIGUE-CRACK CLOSURE



Elber, 1968
Newman, 1976
(FASTRAN)

Beevers, 1979
Suresh & Ritchie, 1982

Paris et al., 1972
Suresh & Ritchie, 1981

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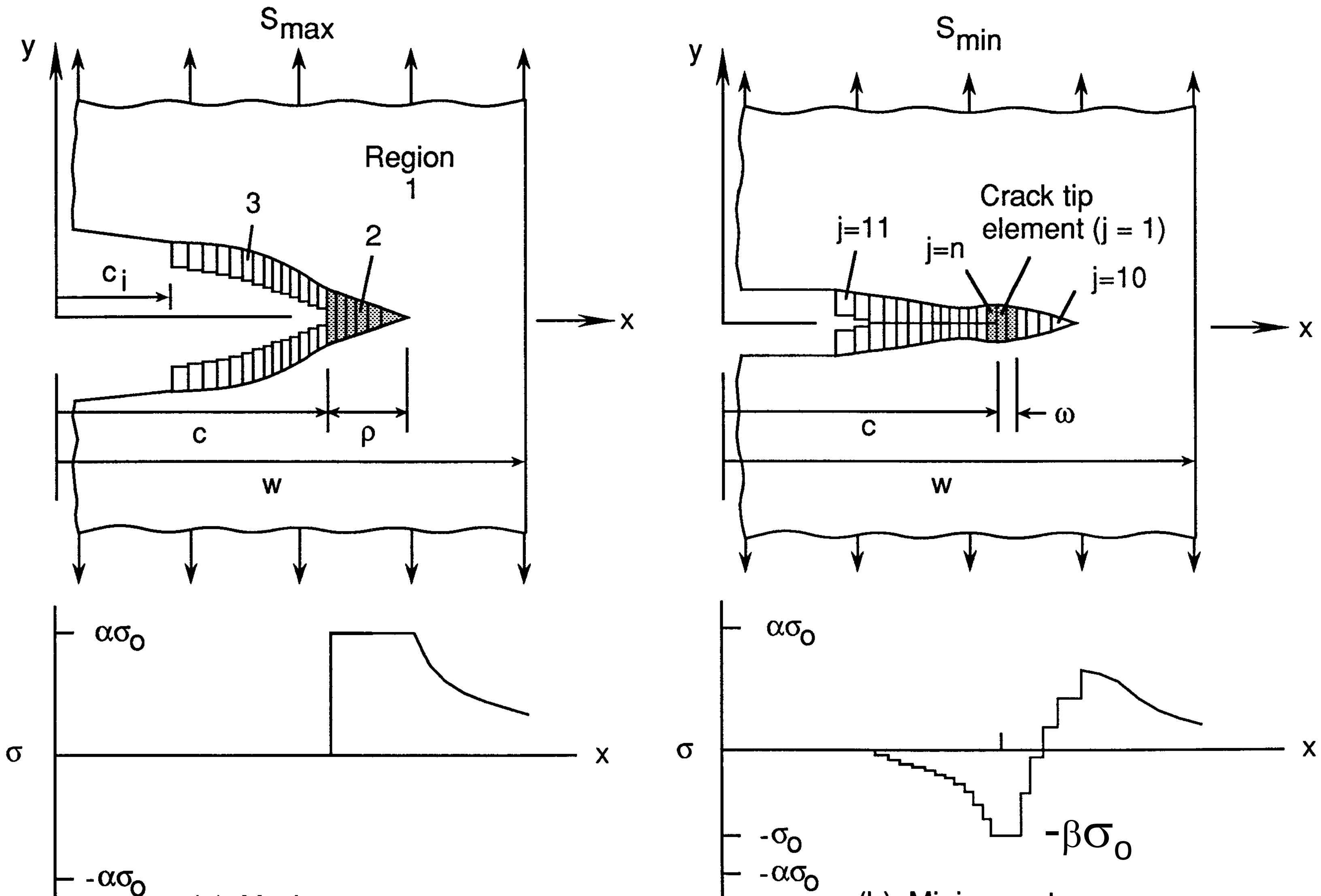
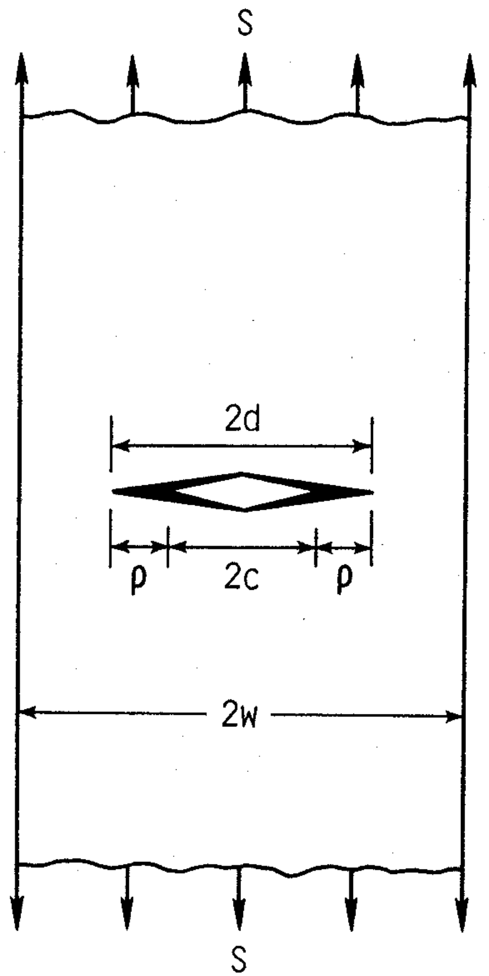
FASTRAN – Crack-Closure Based Life-Prediction Code



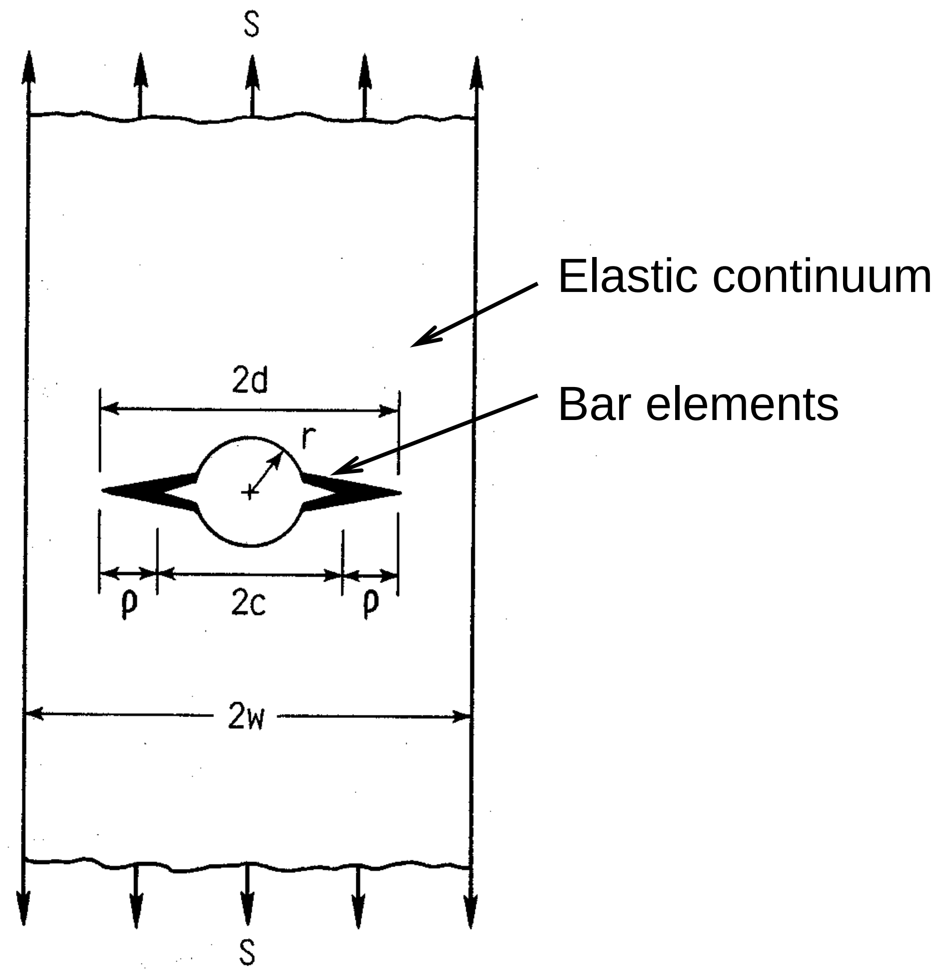
(a) Maximum stress.　　(b) Minimum stress.

MODIFIED DUGDALE MODELS IN FASTRAN



(a) Center crack

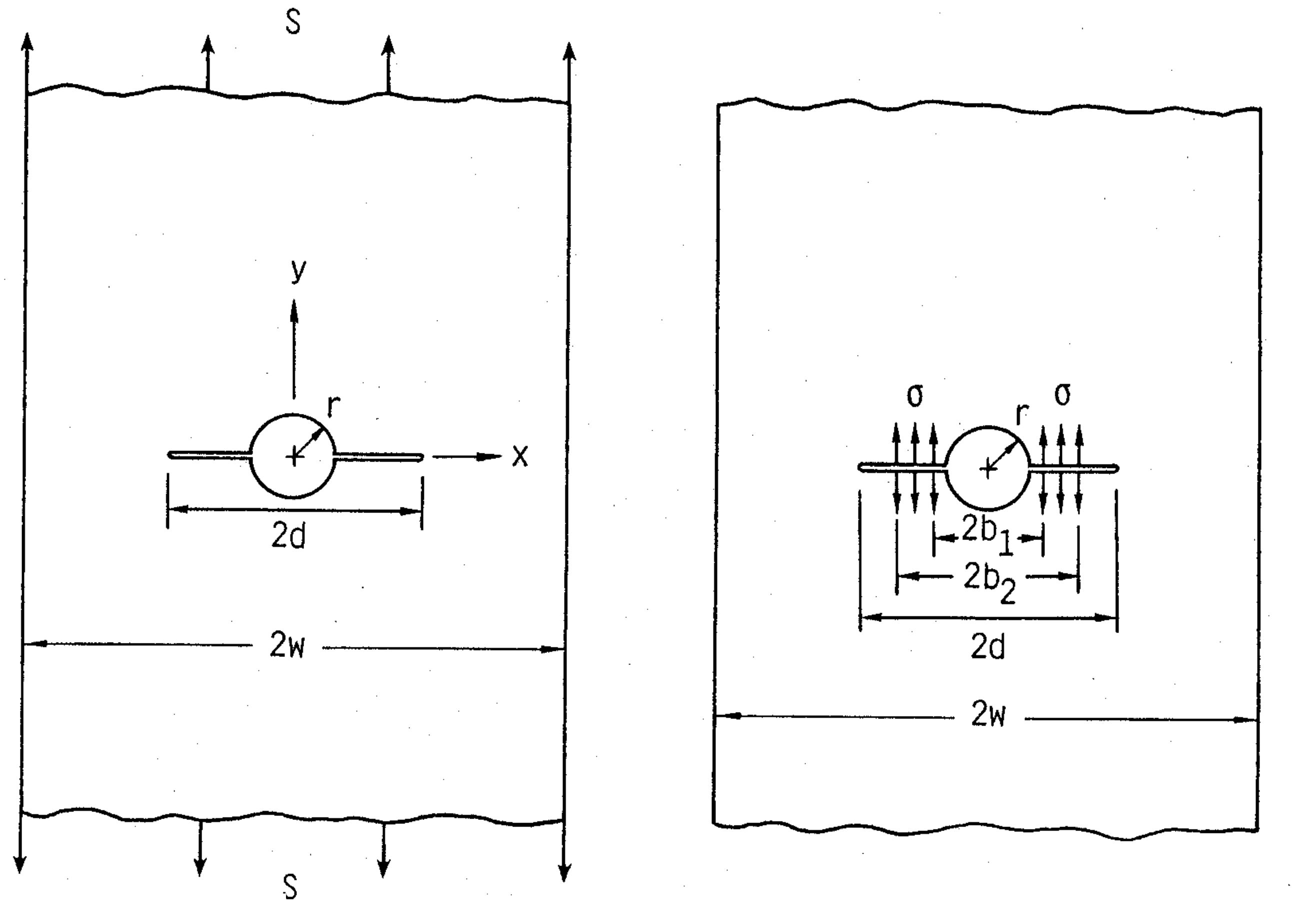
NTYP = 1



(b) Cracks from hole

NTYP = -4

BASIC CRACK SOLUTIONS REQUIRED FOR CLOSURE MODEL



(a) Uniform stress (b) Partially-loaded crack

Crack solutions:

$K_s = f_s(S,d,r,w)$

$V_s = g_s(S,d,r,w,x)$

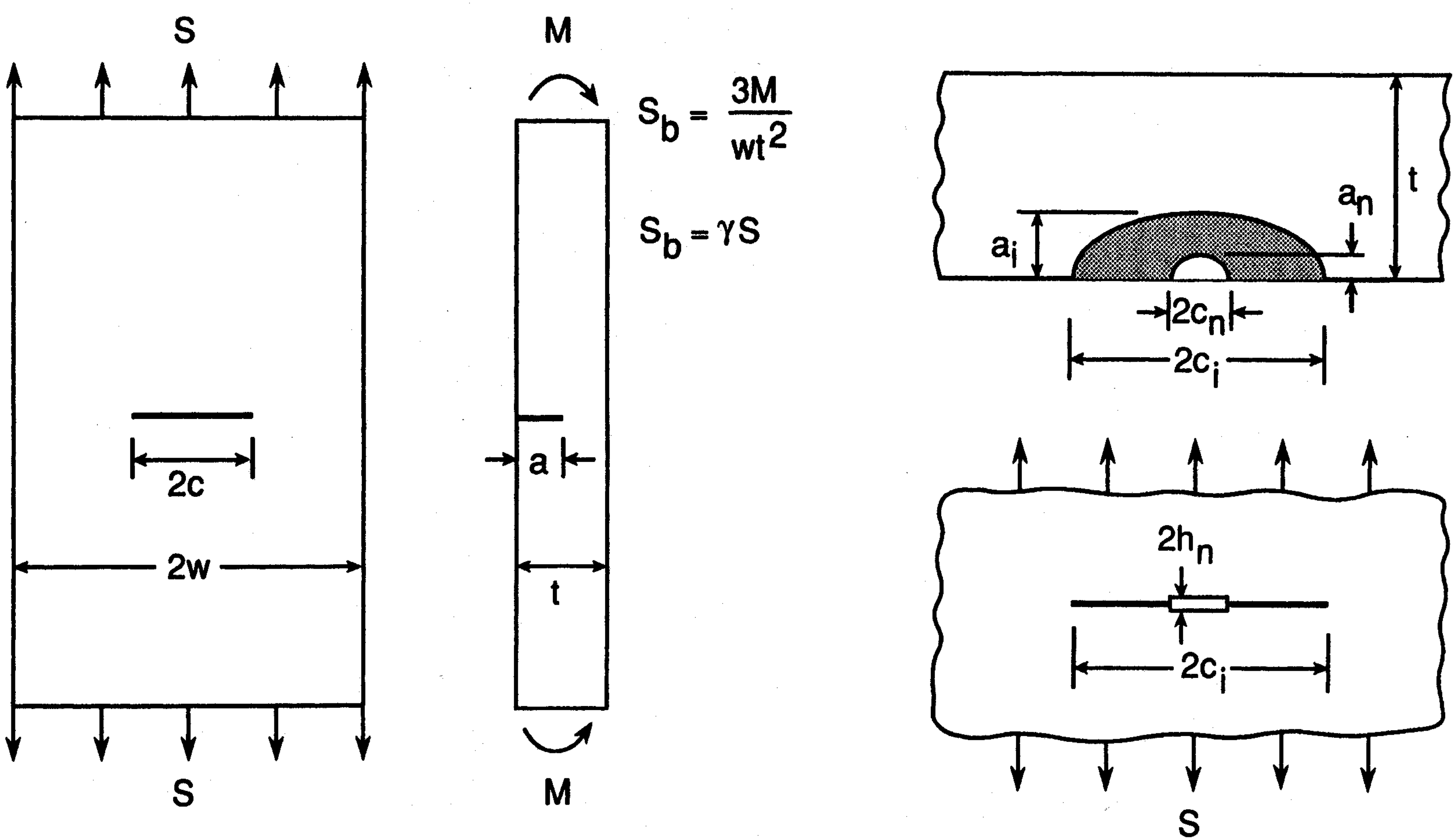
$K_\sigma = f_\sigma(\sigma,d,r,w,b_i,x)$

$V_\sigma = g_\sigma(\sigma,d,r,w,b_i,x)$

FASTRAN Version 5.4+

- Plastic-zone region refined (20 elements in plastic zone instead of 10 elements, like STRIPY model in NASGRO)
- Crack-growth increments (Δc^*) reduced to 5% of cyclic-plastic-zone size instead of 20% (only used for NMAX > 100)
- New crack-opening-stress function developed to fit the refined model (slight increase in crack-opening stresses) for steady-state constant-amplitude loading
- NMAX input (normally set to 300 to 1000), but enables cycle-by-cycle calculations with NMAX = 1 (recommended)
- K-analogy activated for all 2D and 3D crack configurations
- Residual strength (S_n/σ_u) output as function of crack length
- Spectrum loading (NFOPT = 8, 9 and 10) output in cycles and blocks or flights for NREP (repetitions of flight schedule)

CRACK SOLUTION INPUT REQUIRED FOR FASTRAN

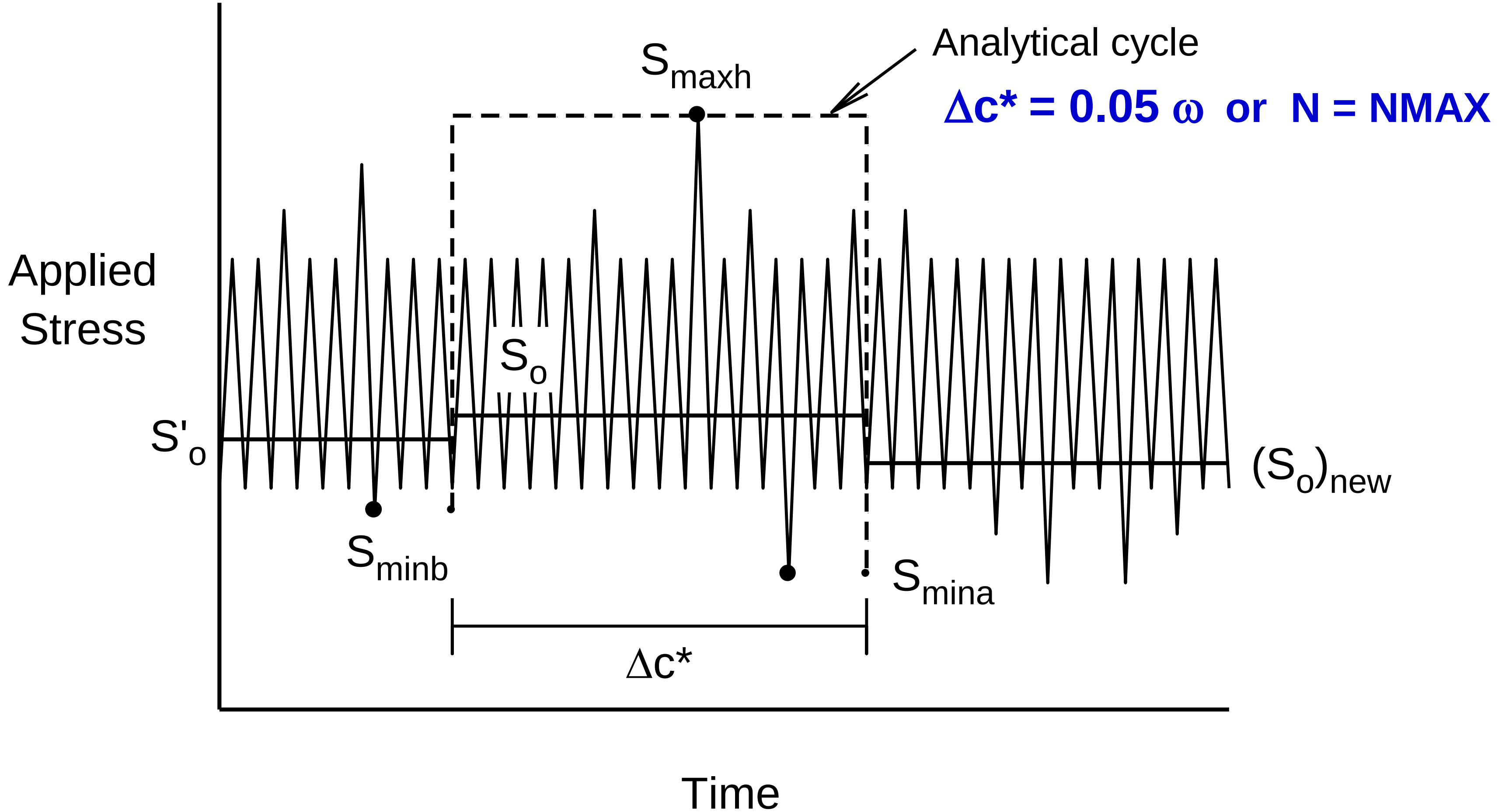


(a) Tension (b) Bending (c) Crack and starter notch

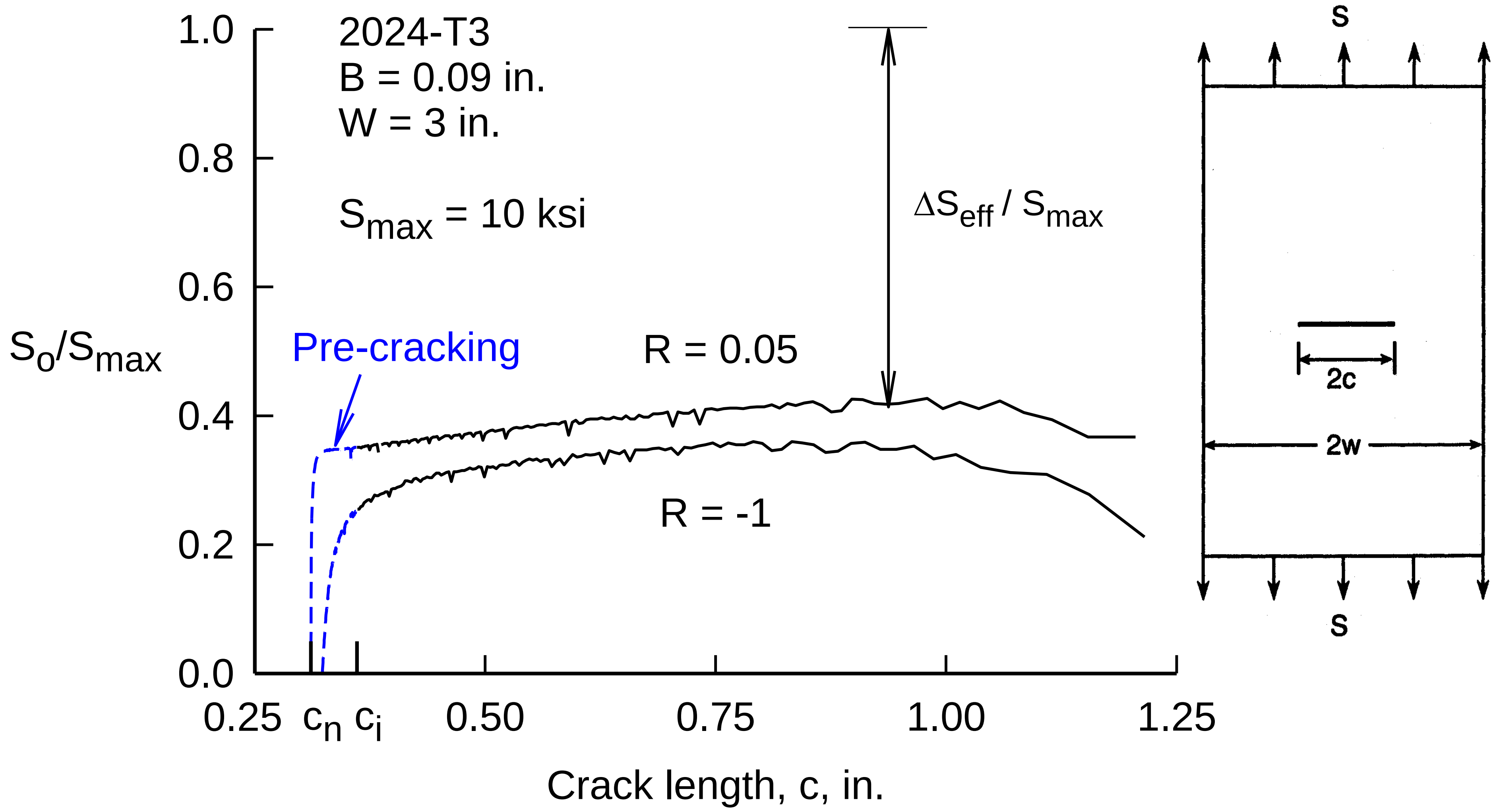
NTYP = 1 **NTYP = 0; LTYP = 1** **Pre-cracking option**

MECHANICS OF THE ANALYTICAL CYCLE IN FASTRAN

FASTRAN Version 5.4+ (recommend cycle-by-cycle, NMAX=1)



CALCULATED CRACK-OPENING STRESSES AT A LOW APPLIED STRESS LEVEL (MIDDLE-CRACK TENSION; NTYP = 1)



CRACK-OPENING STRESSES UNDER CONSTANT-AMPLITUDE LOADING

$$S_o/S_{max} = f(R, S_{max}/\sigma_o, \alpha, \Delta c/c)$$

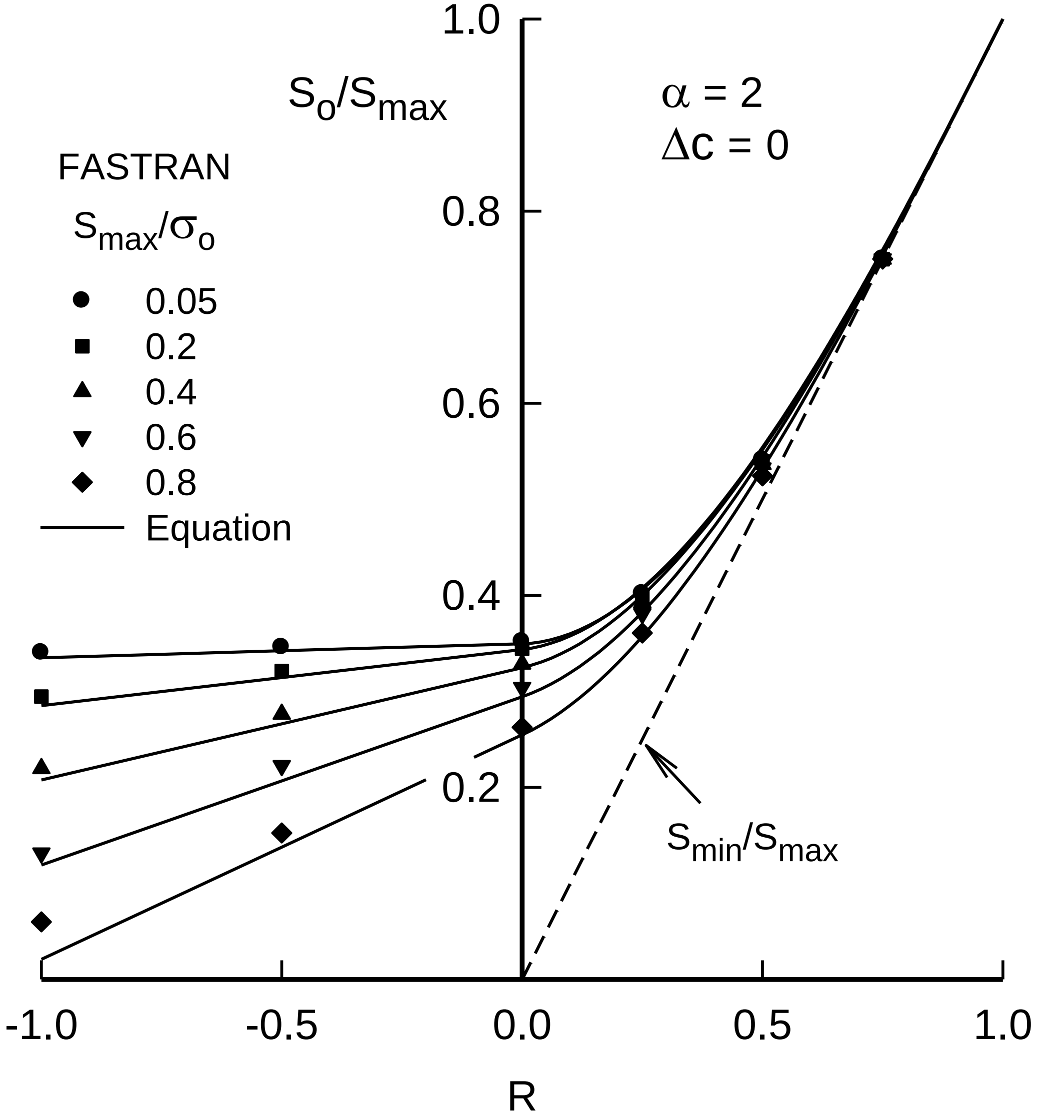
$R = S_{min}/S_{max}$

$\sigma_o = (\sigma_{ys} + \sigma_{ult})/2$

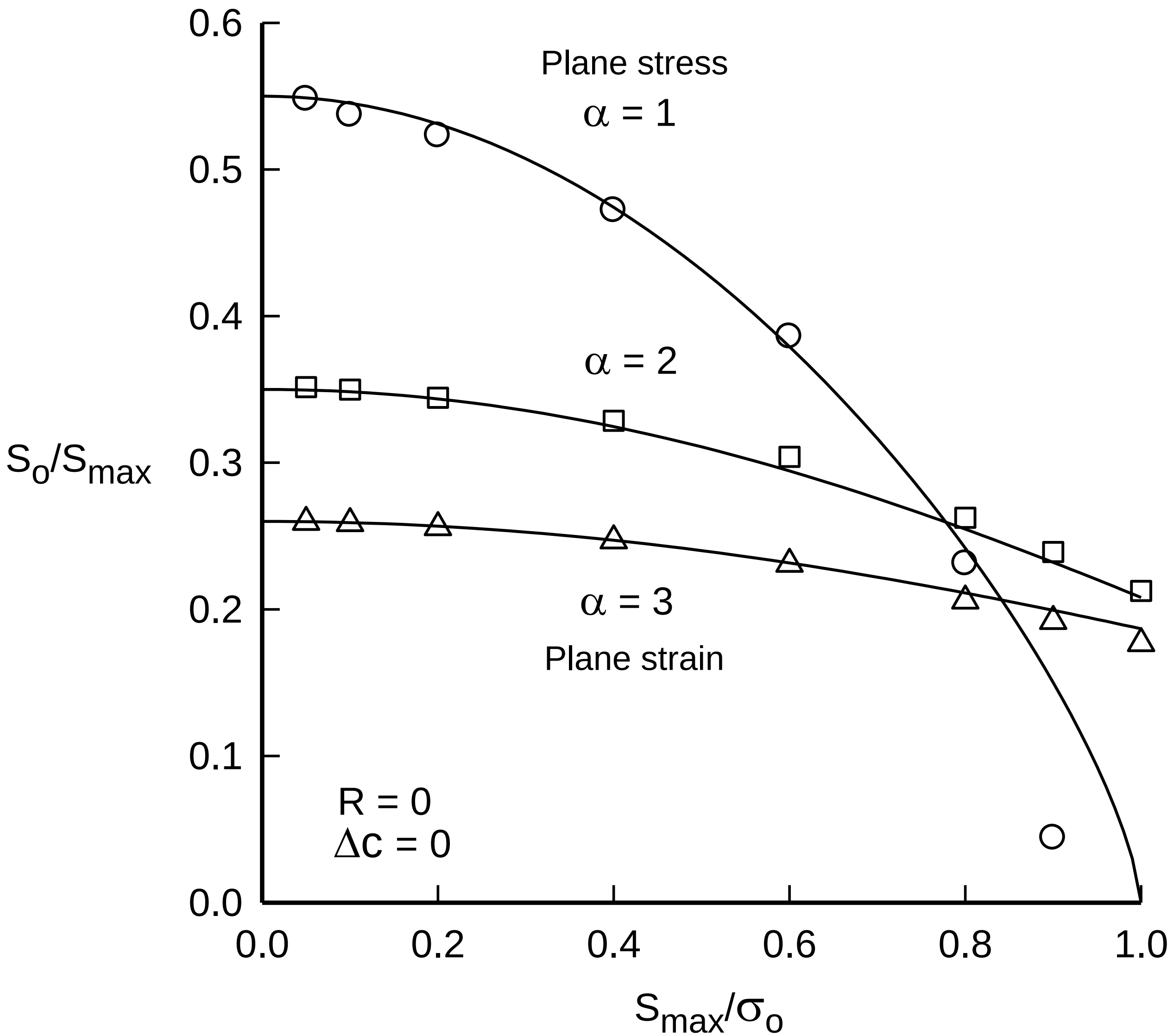
$\alpha = 1$ for plane-stress conditions

$\alpha = 3$ for plane-strain conditions

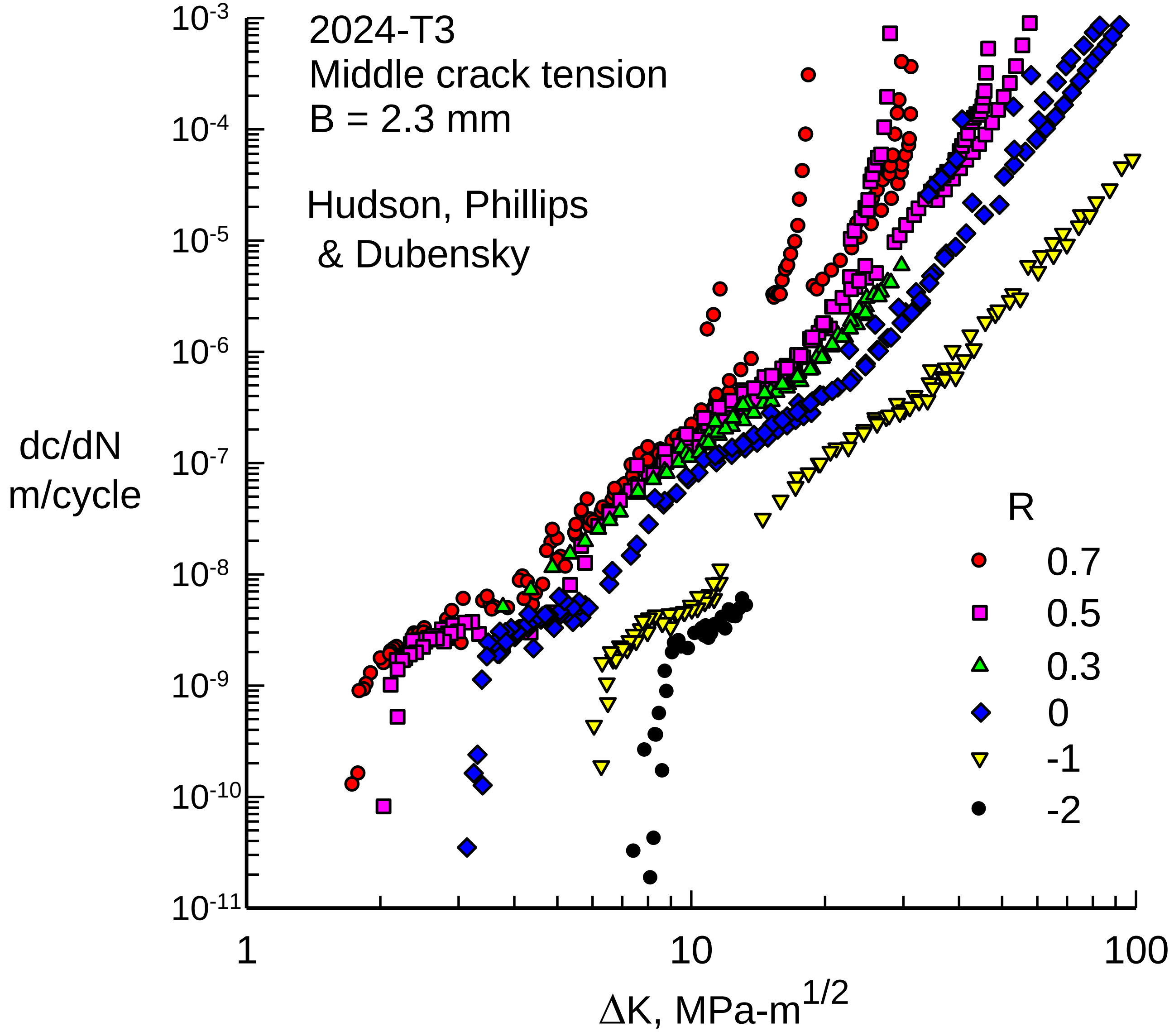
CRACK-OPENING STRESSES AS A FUNCTION OF STRESS RATIO FOR A HIGH CONSTRAINT FACTOR



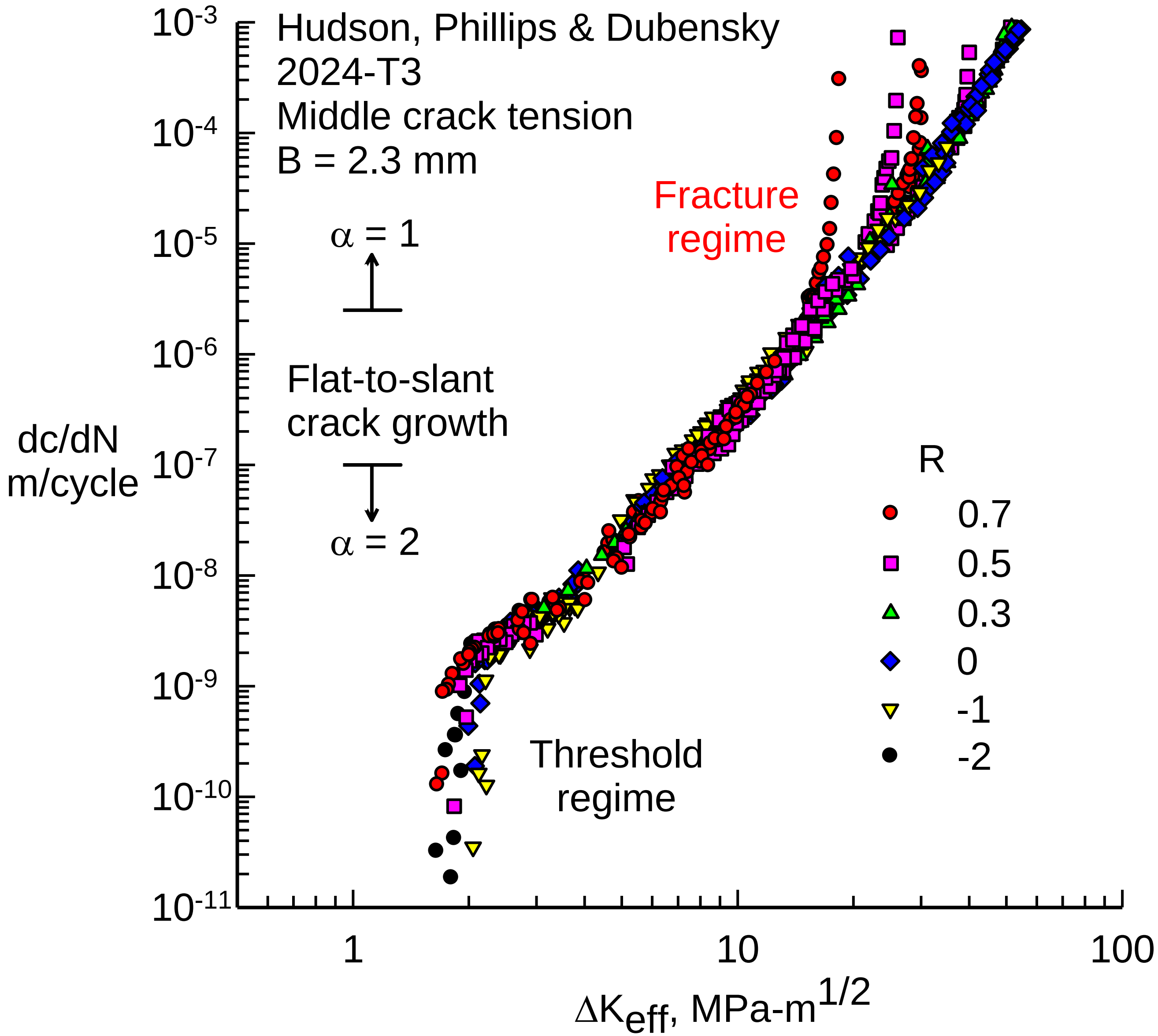
CRACK-OPENING STRESSES AS A FUNCTION OF APPLIED STRESS FOR VARIOUS CONSTRAINT FACTORS



FATIGUE-CRACK-GROWTH RATES USING LEFM ANALYSES

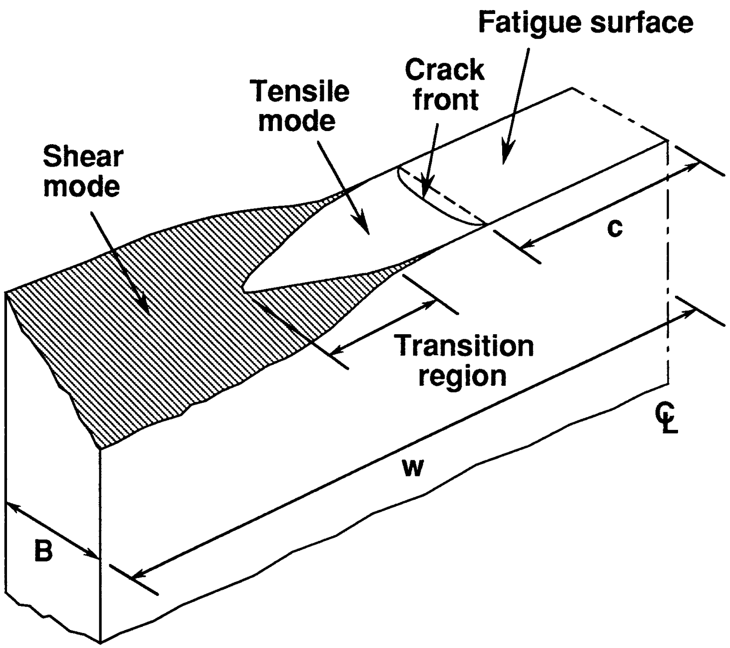


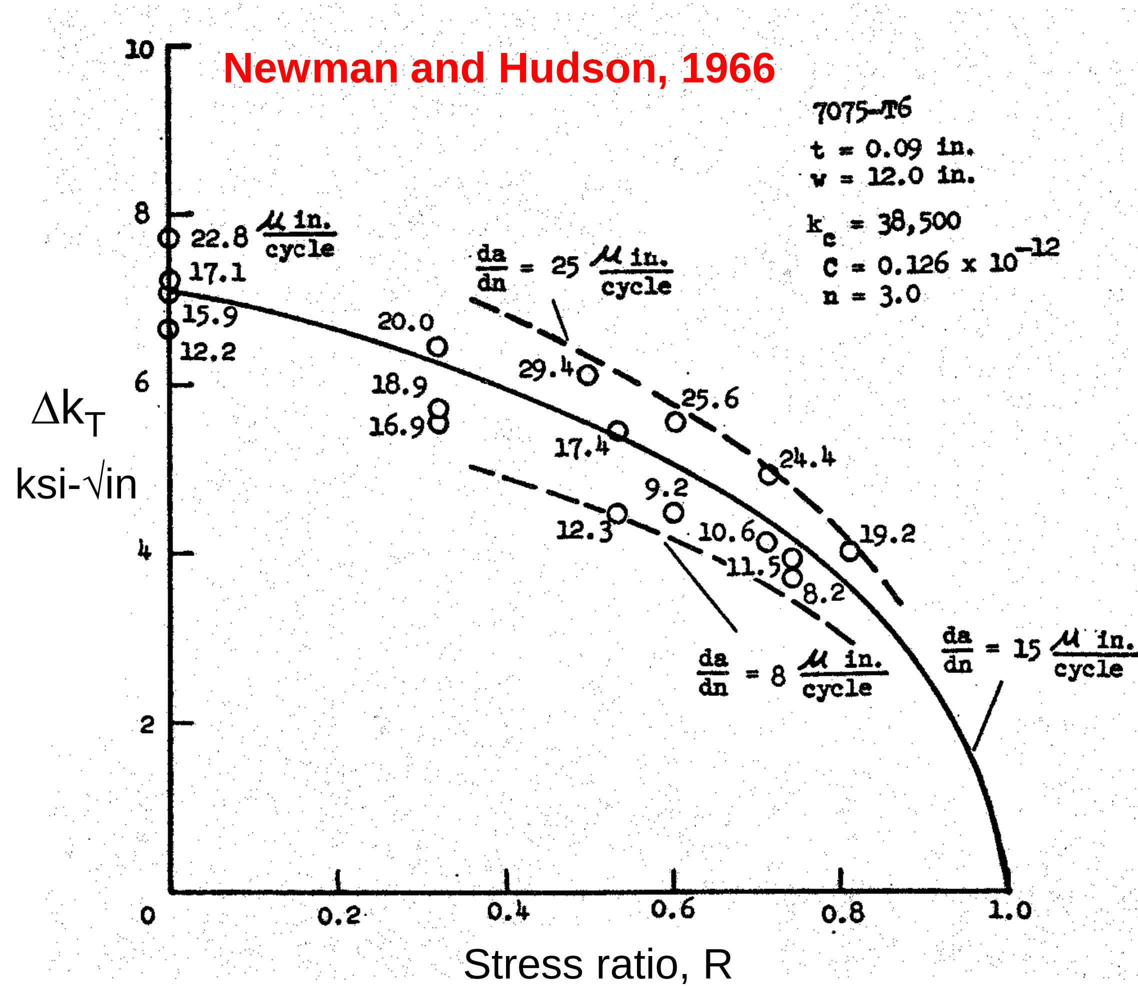
FATIGUE-CRACK-GROWTH RATES CORRELATION USING CRACK-CLOSURE ANALYSES



FLAT-TO-SLANT FATIGUE-CRACK GROWTH

Schijve (1966): Observed transition occurs at “constant rate”



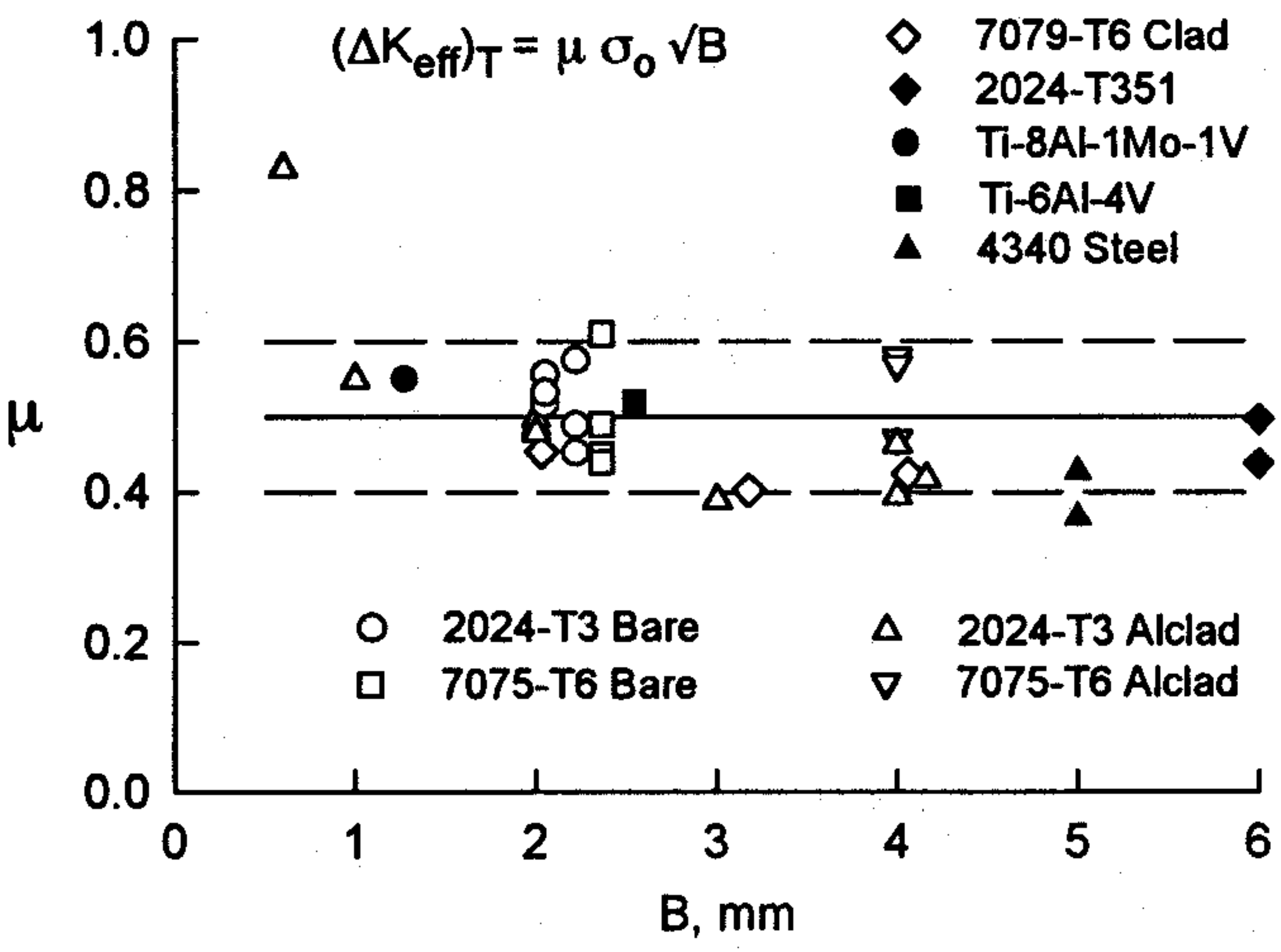


Constraint loss appears to occur on M(T) specimens, but not on deep-cracks in C(T) or bending specimens

FLAT-TO-SLANT FATIGUE-CRACK GROWTH TRANSITION

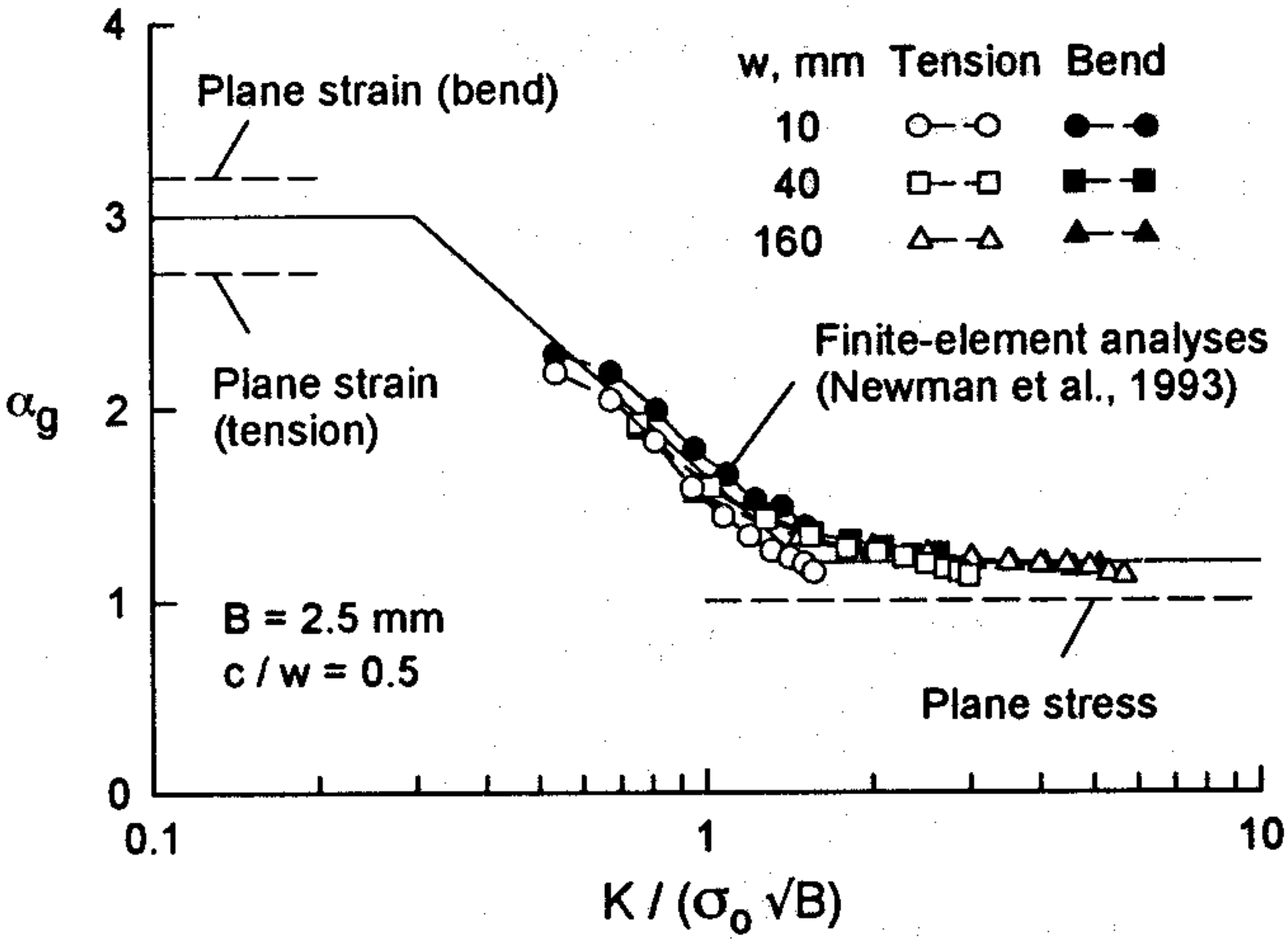
Newman, 1992

M(T) specimens:



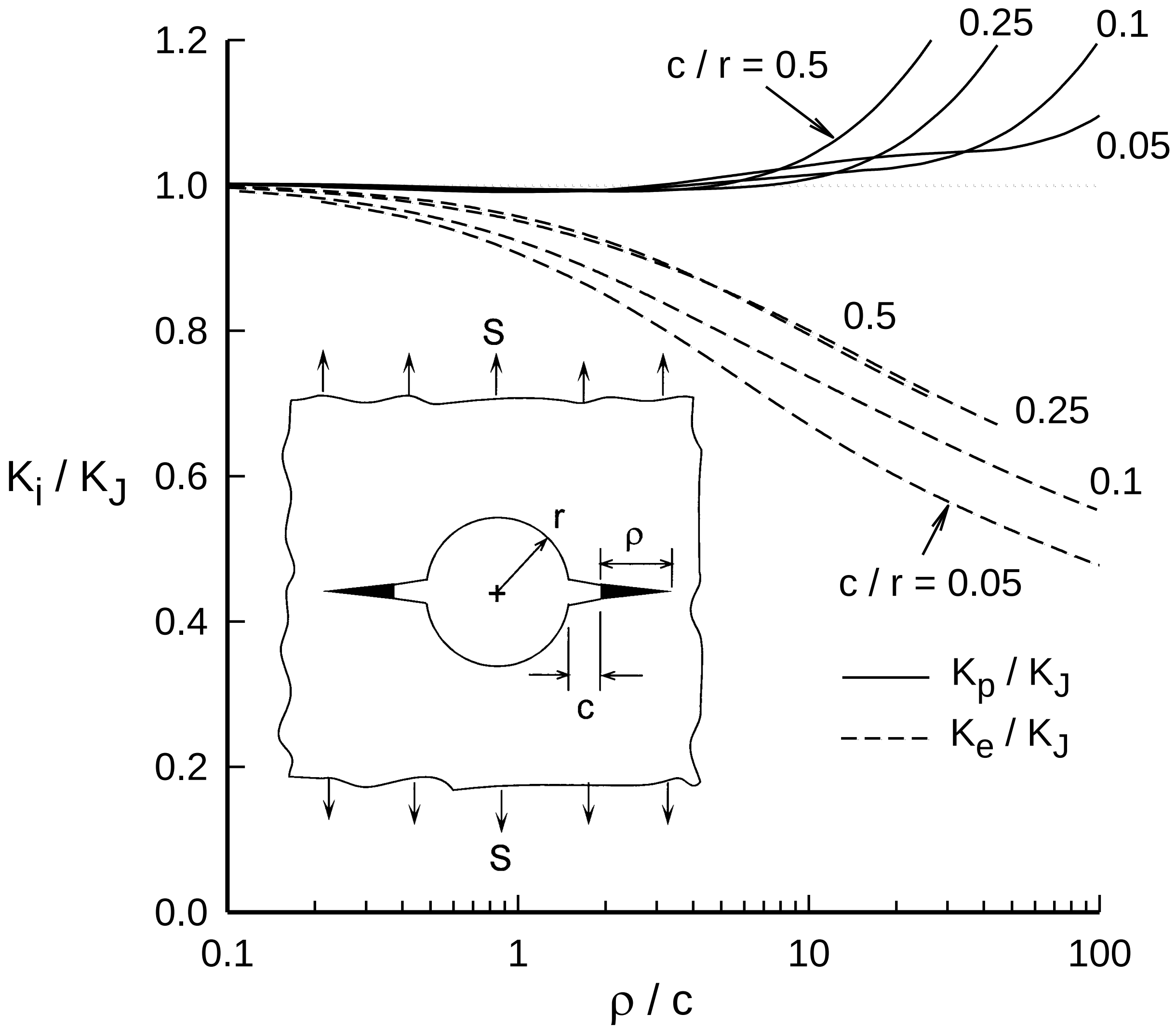
CONSTRAINT EFFECTS IN THREE-DIMENSIONAL CRACKED BODIES

Newman, Bigelow & Shivakumar, 1993



ELASTIC-PLASTIC STRESS-INTENSITY FACTORS

Newman, 1992



Crack Parameters:

$K_i = S\,(\pi d)^{1/2}\,F(d/r)$

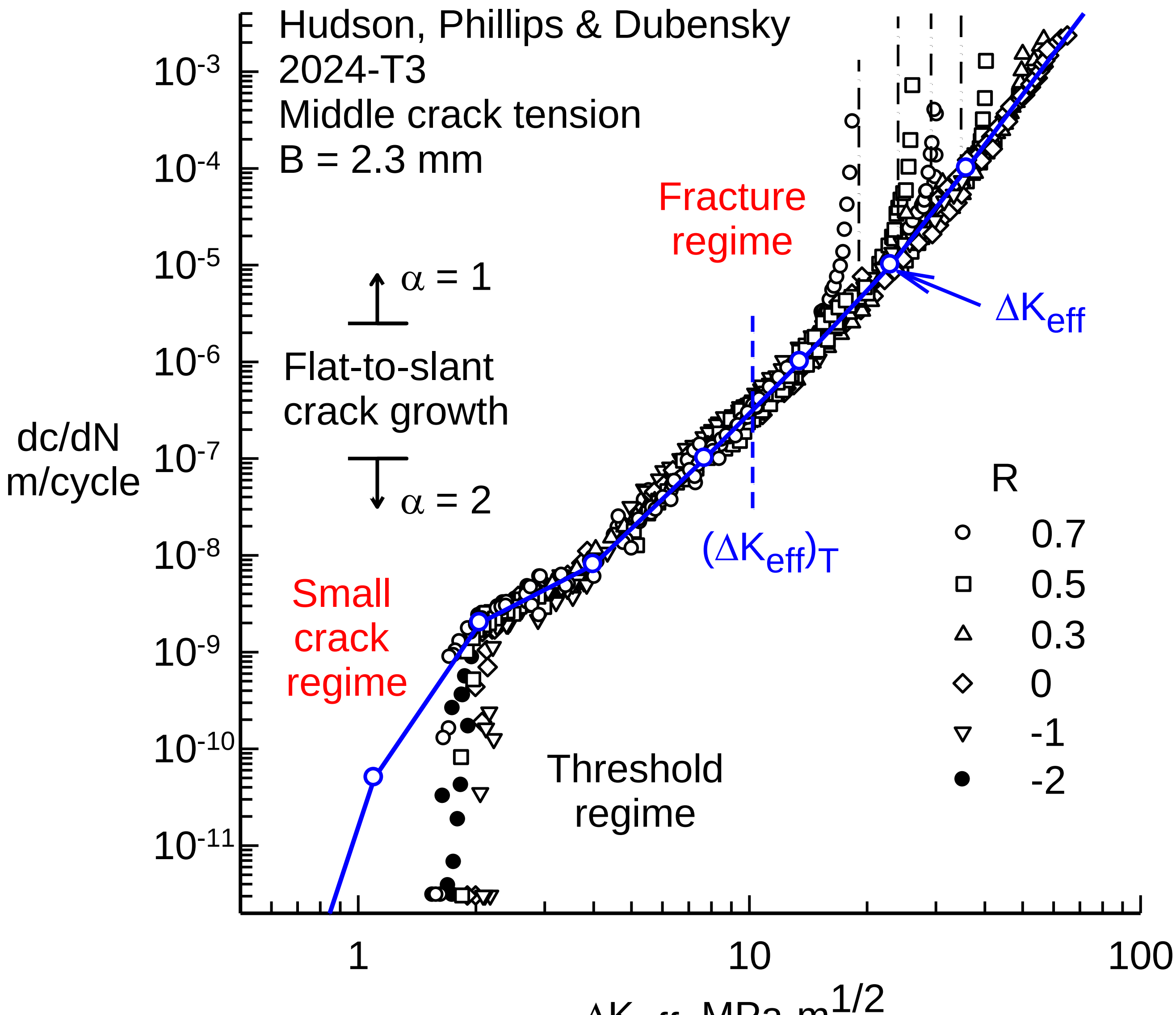
where $d = c + \gamma\rho$

$\gamma = 0$ elastic

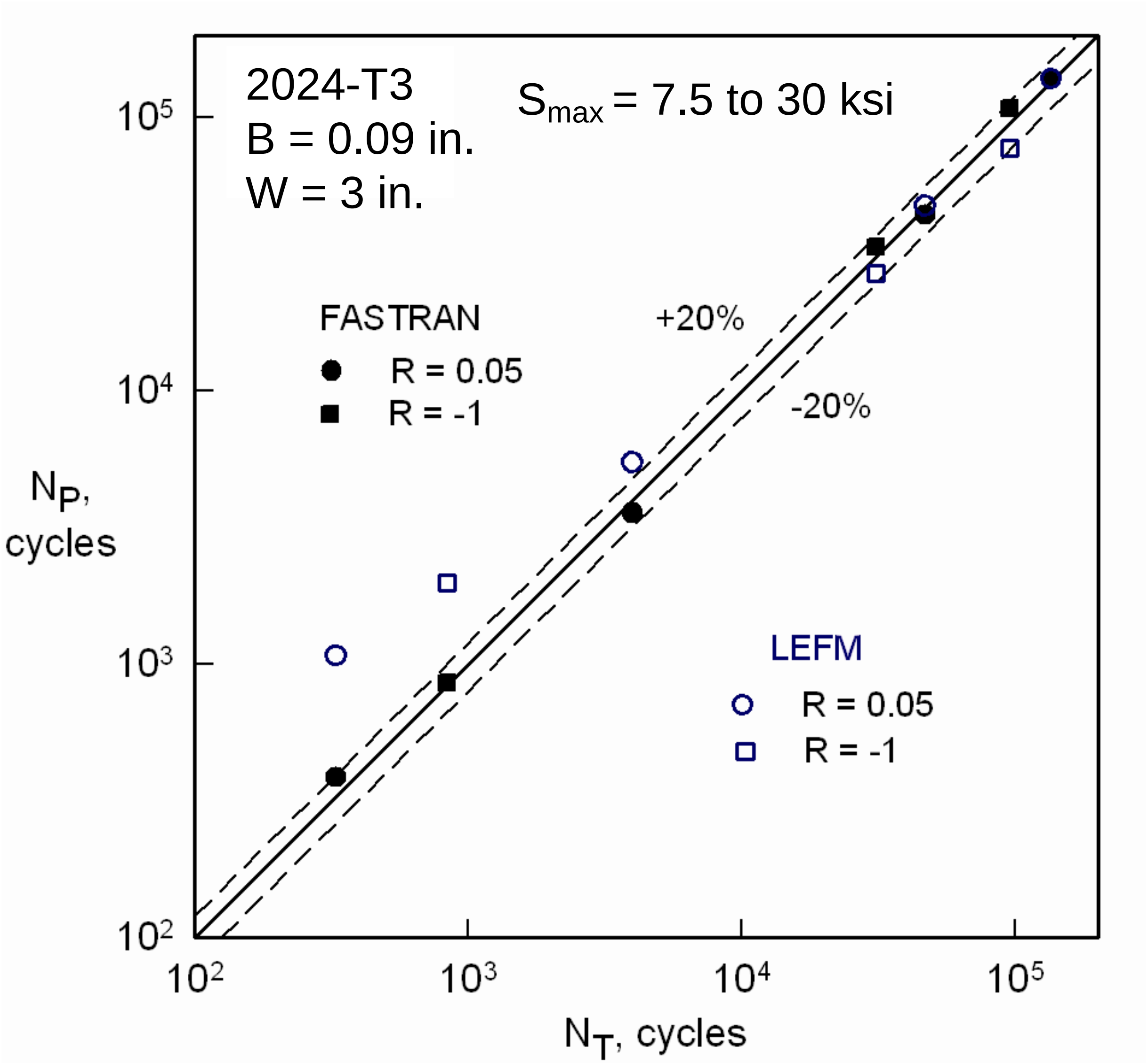
$\gamma = 1/4$ elastic-plastic

$J = K_p^2/E$

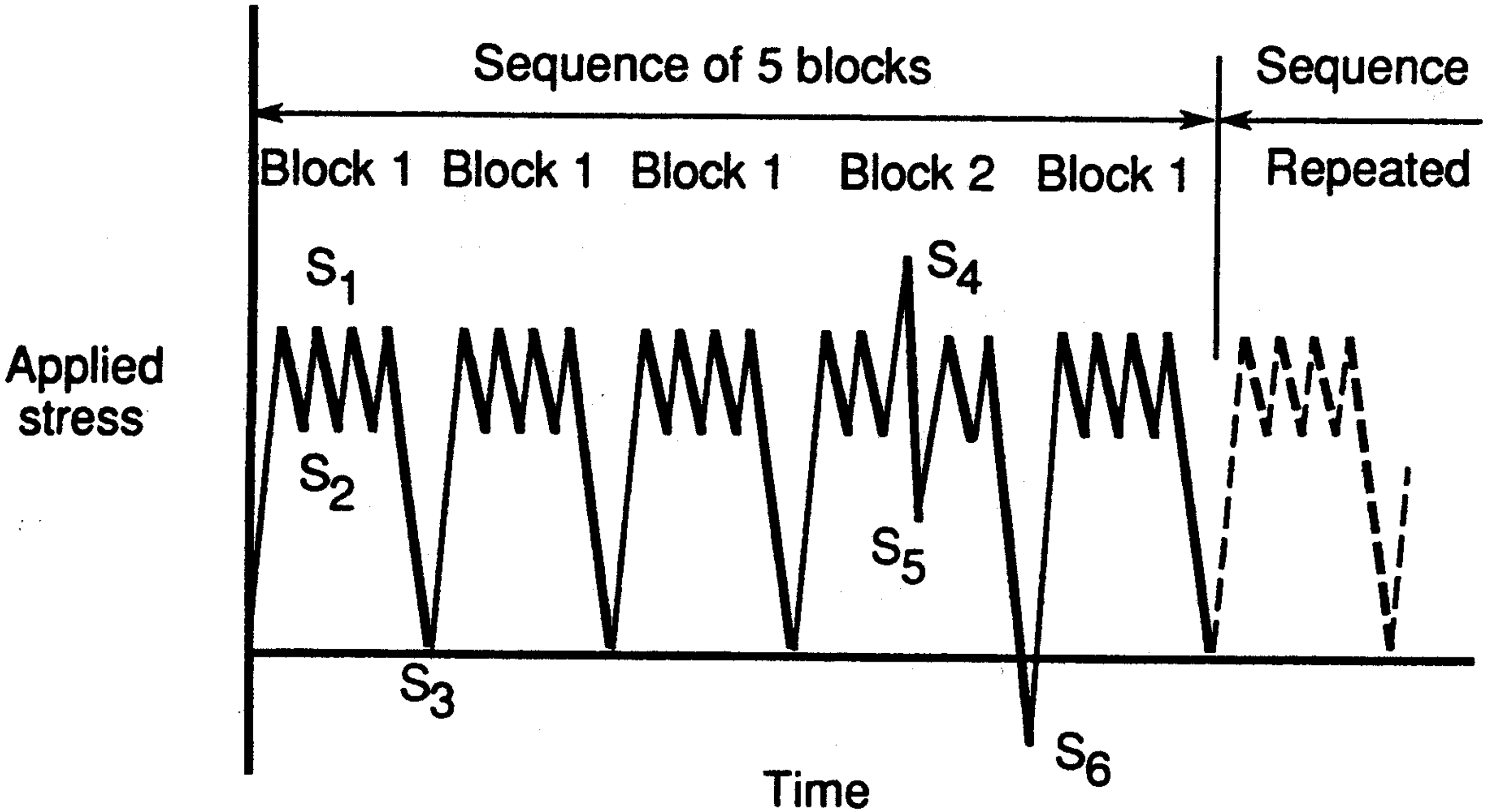
CRACK-CLOSURE ANALYSES OF 2024-T3 ALUMINUM ALLOY



COMPARISON OF MEASURED AND PREDICTED CRACK GROWTH USING LEFM AND FASTRAN



VARIABLE-AMPLITUDE LOADING OPTION (NFOPT = 1)



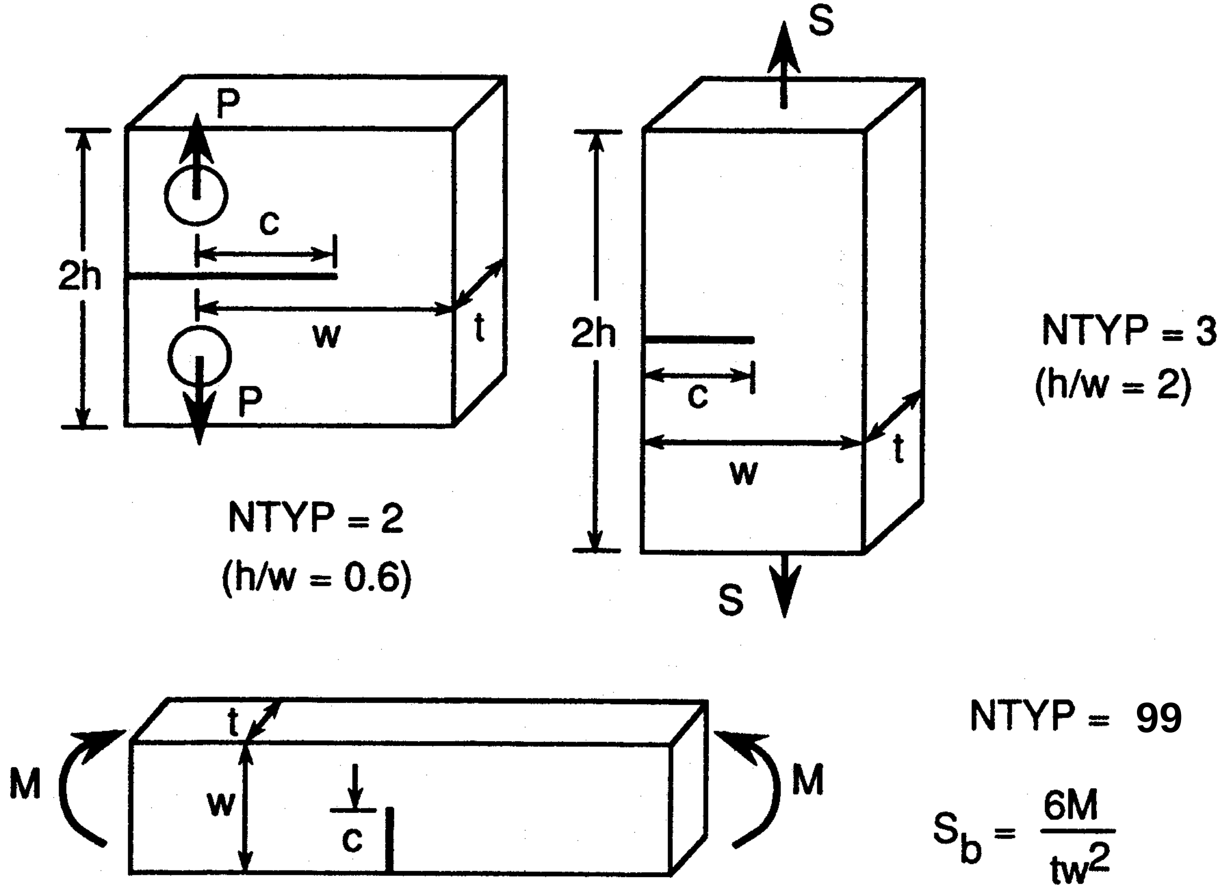
SPECTRUM LOADING OPTIONS IN FASTRAN

- **TWIST or MINI-TWIST - Transport Spectra** (NFOPT = 2 or 3)
- **FALSTAFF - Fighter Spectra** (NFOPT = 4)
- **SPACE SHUTTLE Load Spectra** (NFOPT = 5)
- **Gaussian (R ~ -1) Load Sequence** (NFOPT = 6)
- **Felix & Helix Helicopter Flight-Load Sequence** (NFOPT = 7)
- **Spectrum Read from List of Stress Points** (NFOPT = 8)
- **Spectrum Read from Flight-by-Flight Loading** (NFOPT = 9)
- **Spectrum Read from Flight Schedule** (NFOPT = 10)

CRACK CONFIGURATION OPTIONS IN FASTRAN

- **Two-dimensional crack configurations (15)**
  - Middle-crack tension
  - Compact and bend type specimens
  - Crack(s) from an open hole
  - Crack in a pressurized cylinder
  - Periodic array of cracks at holes
  - User defined crack configuration
- **Three-dimensional crack configurations (11)**
  - Surface crack (tension or bending loads)
  - Surface or corner crack(s) at an open hole
  - AGARD small-crack specimen
  - Periodic array of surface or corner cracks at pin-loaded holes

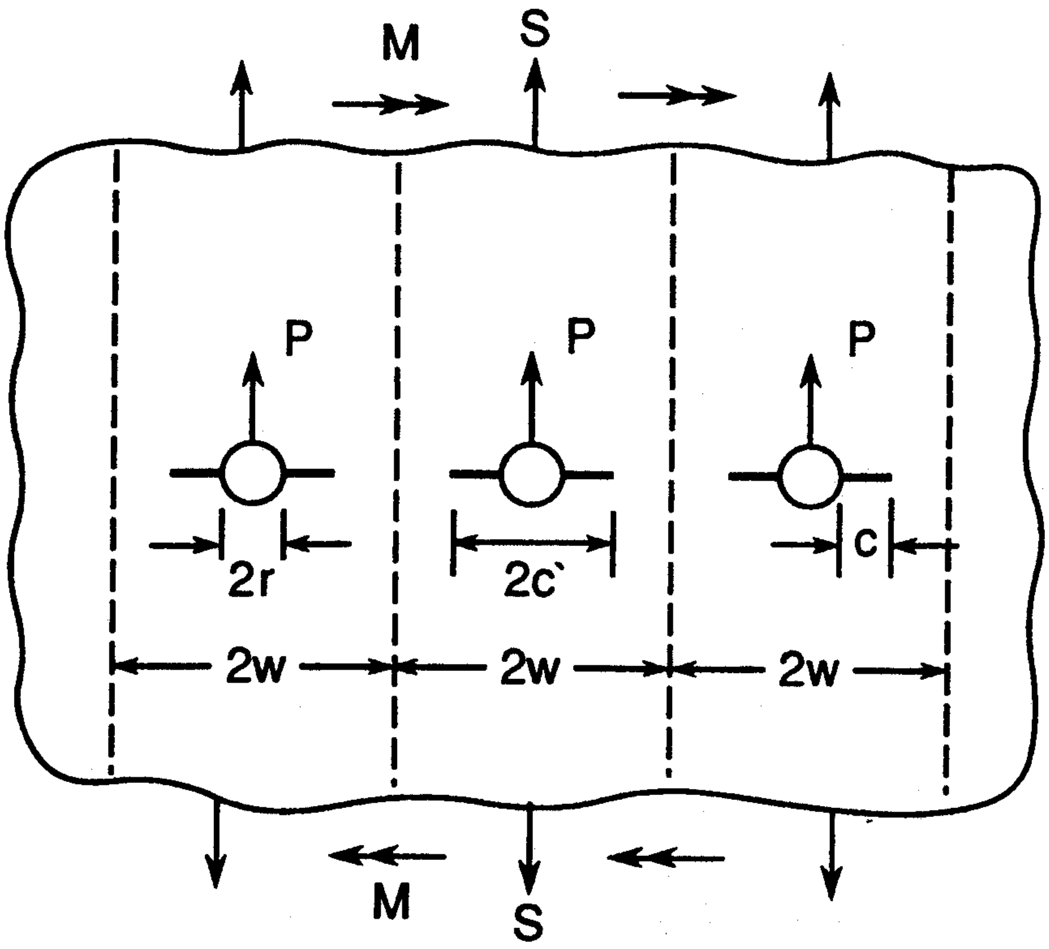
LABORATORY SPECIMENS



Example of user defined crack configuration

(NTYP = -99 Crack(s) from hole)

RIVETED AIRCRAFT JOINT CRACK CONFIGURATION



NTYP = -11

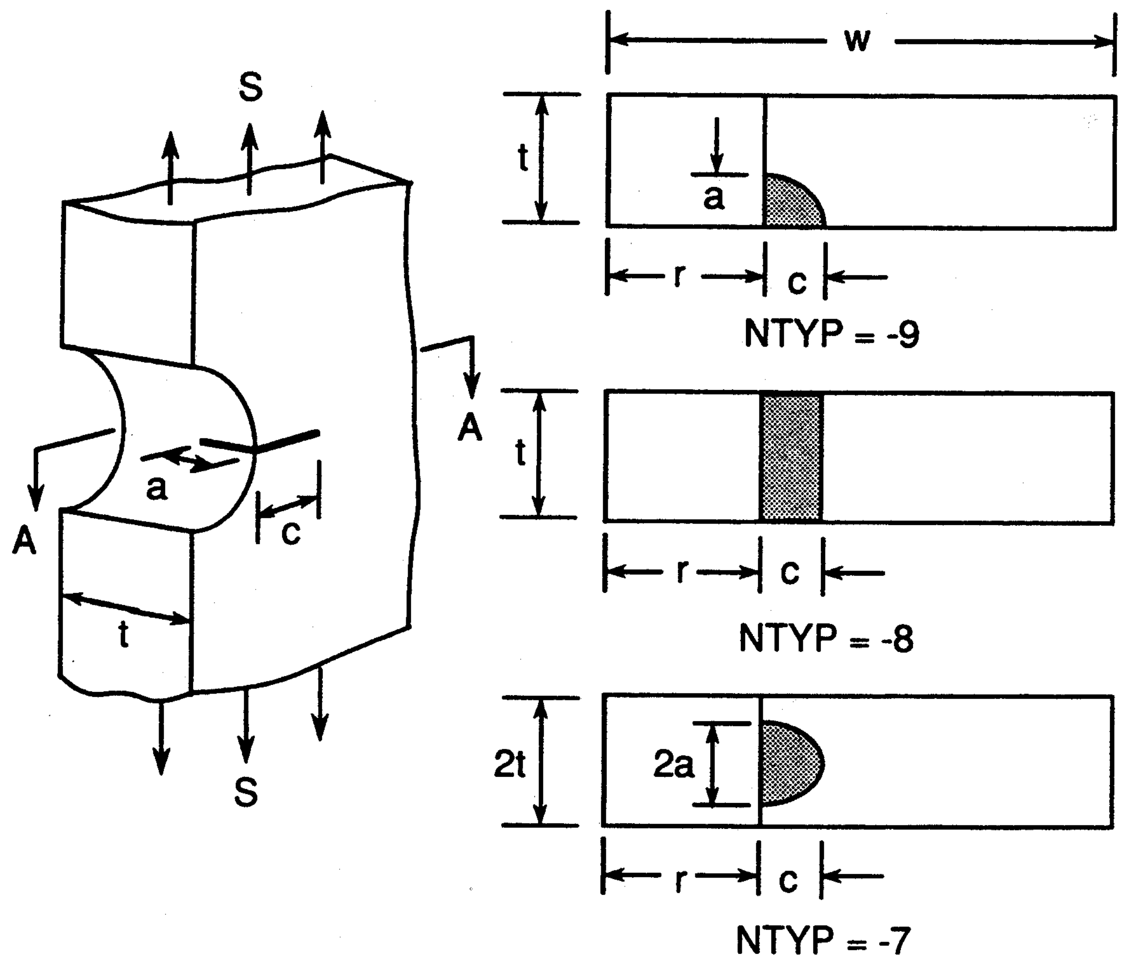
(P = M = 0)

NTYP = -10

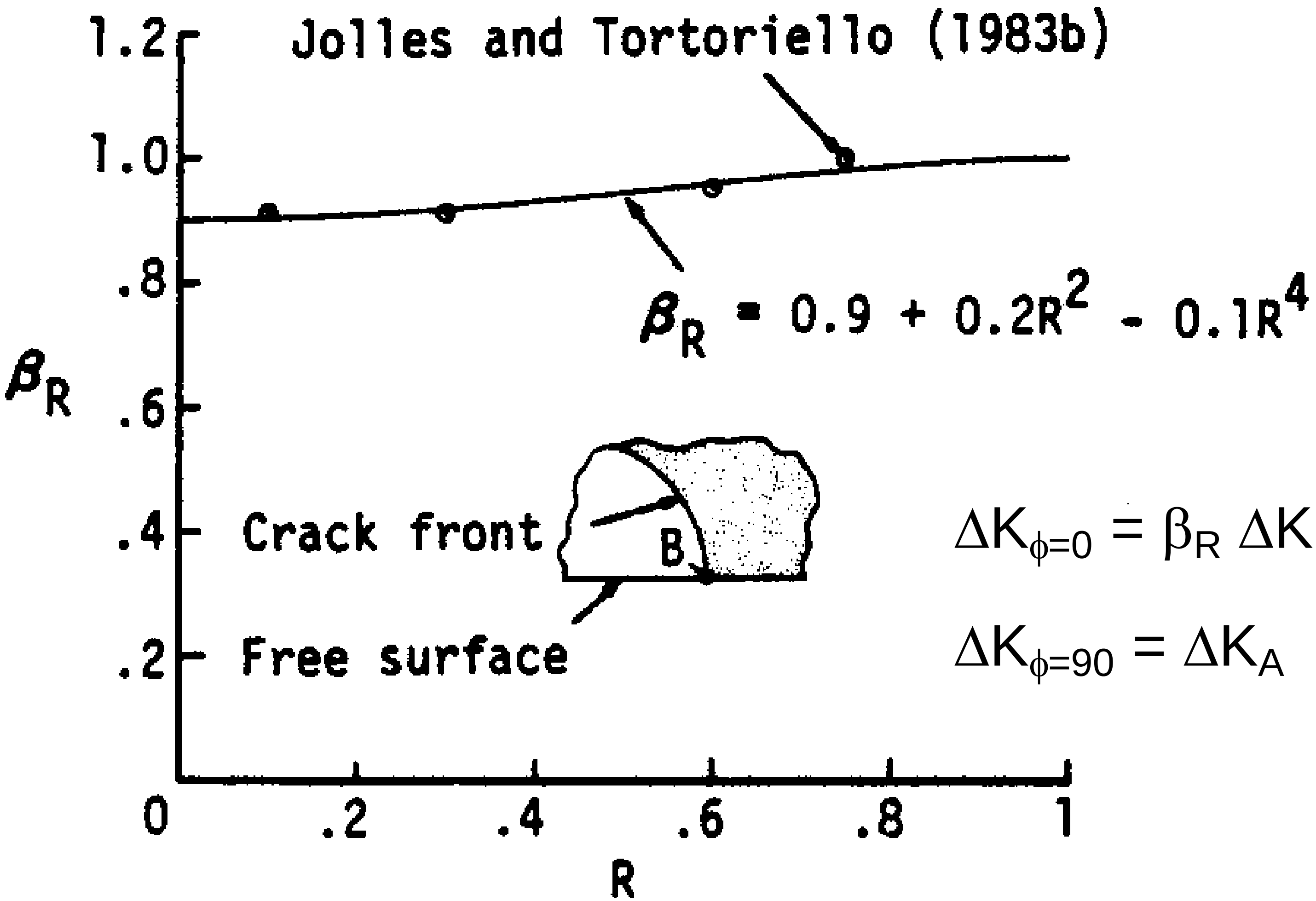
($S_b = \gamma S$)

c` = r + c

AGARD SMALL-CRACK SPECIMEN



CRACK-CLOSURE CORRECTION FOR FREE SURFACE



$$\Delta K_{\phi=0} \doteq \beta_R \, \Delta K_B$$

$$\Delta K_{\phi=90} = \Delta K_A$$

FATIGUE-CRACK GROWTH RATE OPTIONS

- **Equation:** $dc/dN = c_1 \, \Delta K_{eff}^{C_2} \; f(\Delta K_{th}) \, / \, g(K_c)$

  - $f(\Delta K_{th}) = 1 - (\Delta K_o / \Delta K_{eff})^p$

    $\Delta K_o = c_3 \, (1 + c_4 \, R)$ or $\Delta K_o = c_3 \, (1 - R)^{C_4}$

  - $g(K_c) = 1 - (K_{max} / c_5)^q$

- **Table Look-up:** $dc/dN = f(\Delta K_{eff})$ (Max 35 points)

  - $f(\Delta K_{eff}) = c_{1i} \, \Delta K_{eff}^{C_{2i}}$ (i = 1 to 34)

  - $f(\Delta K_{eff}) = c_{1i} \, \Delta K_{eff}^{C_{2i}} \; f(\Delta K_{th}) \, / \, g(K_c)$

- **Crack growth** (da/dN = dc/dN or da/dN # dc/dN)

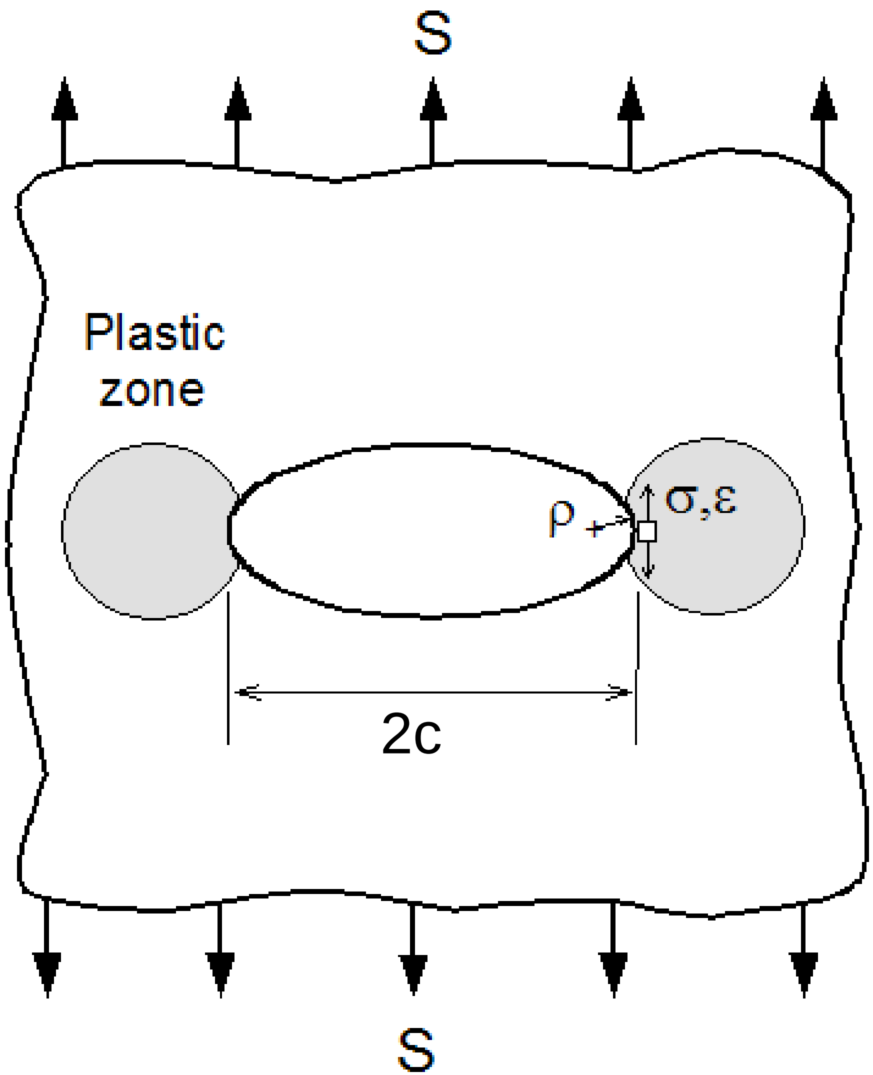
FRACTURE CRITERIA

- **Two-Parameter Fracture Criterion – K_F and m**
  - m = 0 LEFM ($K_c = K_F$ for $S_n < \sigma_{ys}$)
  - m = 1 Plastic-collapse criteria (K_F large)

- **Cyclic fracture toughness exceeded ($K_{max} > C_5$)**

- **Plastic-zone size exceeds net-section region**

Elastic-Plastic Stress- and Strain-Concentration Factors using Neuber's Equation



Neuber (1961):

$$K_\sigma K_\varepsilon = K_T^2$$

$$\sigma \, \varepsilon \, E = \sigma_e^2$$

Hutchinson, Rice (1968) showed that the stress-strain field for a ***crack*** in a non-linear elastic material verified Neuber's equation

Crews (1974) experimentally validated Neuber's equation for ***elliptical hole*** in finite plate under remote uniform stress

Original Two-Parameter Fracture Criterion

- Inglis' stress-concentration equation for elliptical hole,

$$K_T = 1 + 2\sqrt{(c/\rho)}$$

- Neuber's equation: $K_\sigma K_\varepsilon = K_T^2$

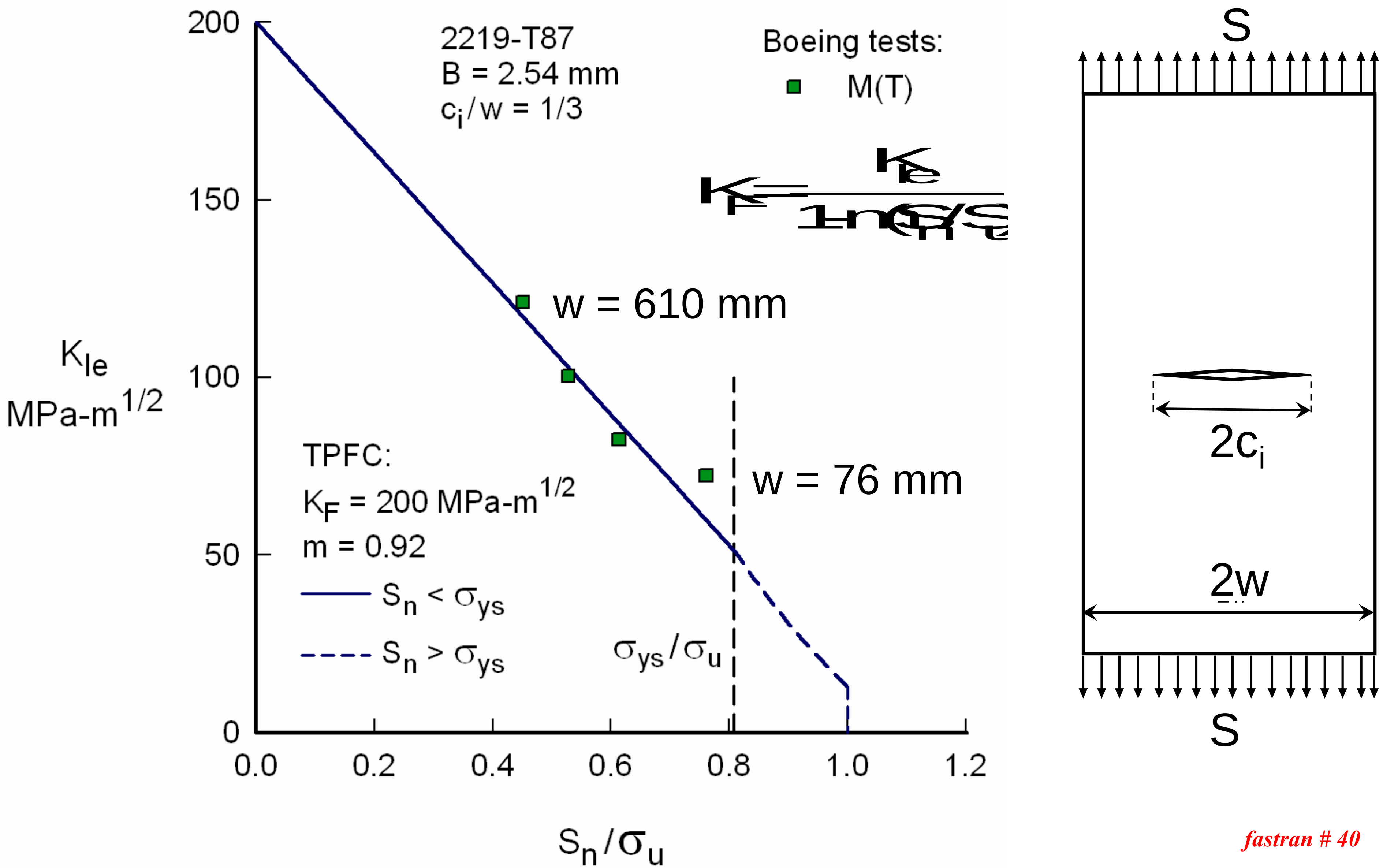
$$K_F = K_{Ie} / \Phi$$

$$\Phi = 1 - m\,(S_n/\sigma_u) \quad \text{for} \quad S_n < \sigma_{ys}$$

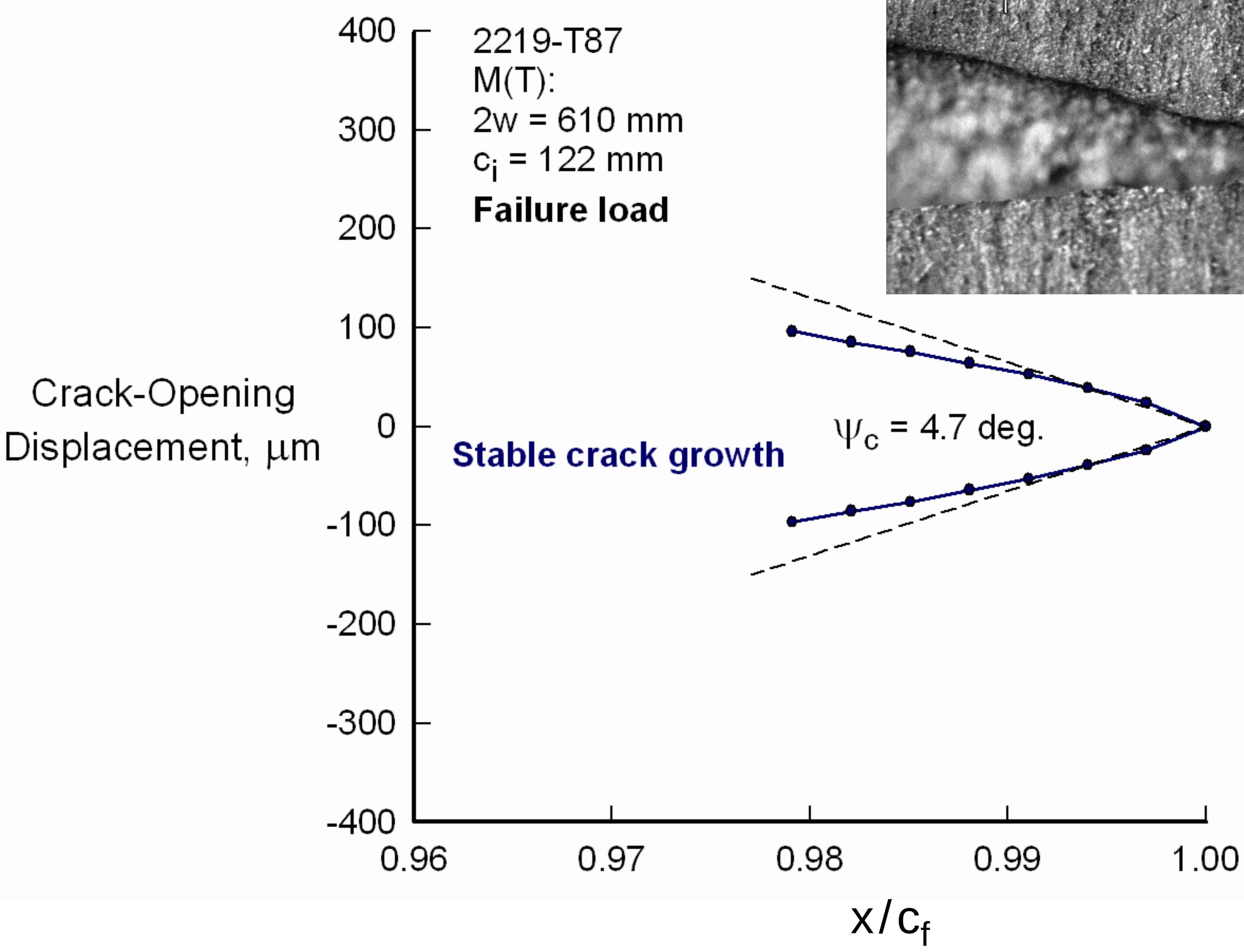
$$\Phi \approx (\sigma_{ys}/S_n)\,[1 - m\,(S_n/\sigma_u)] \quad \text{for} \quad S_n \geq \sigma_{ys}$$

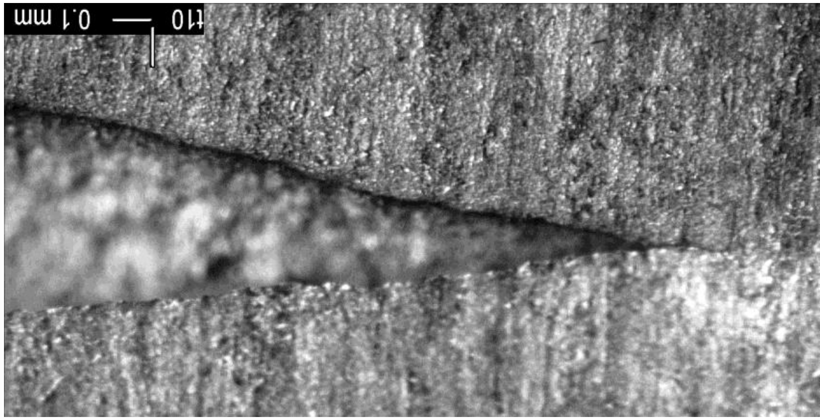
Constraint effects on net-section *NOT* considered !

Two-Parameter Fracture Criterion Analysis on 2219-T87 Aluminum Alloy M(T) Specimens



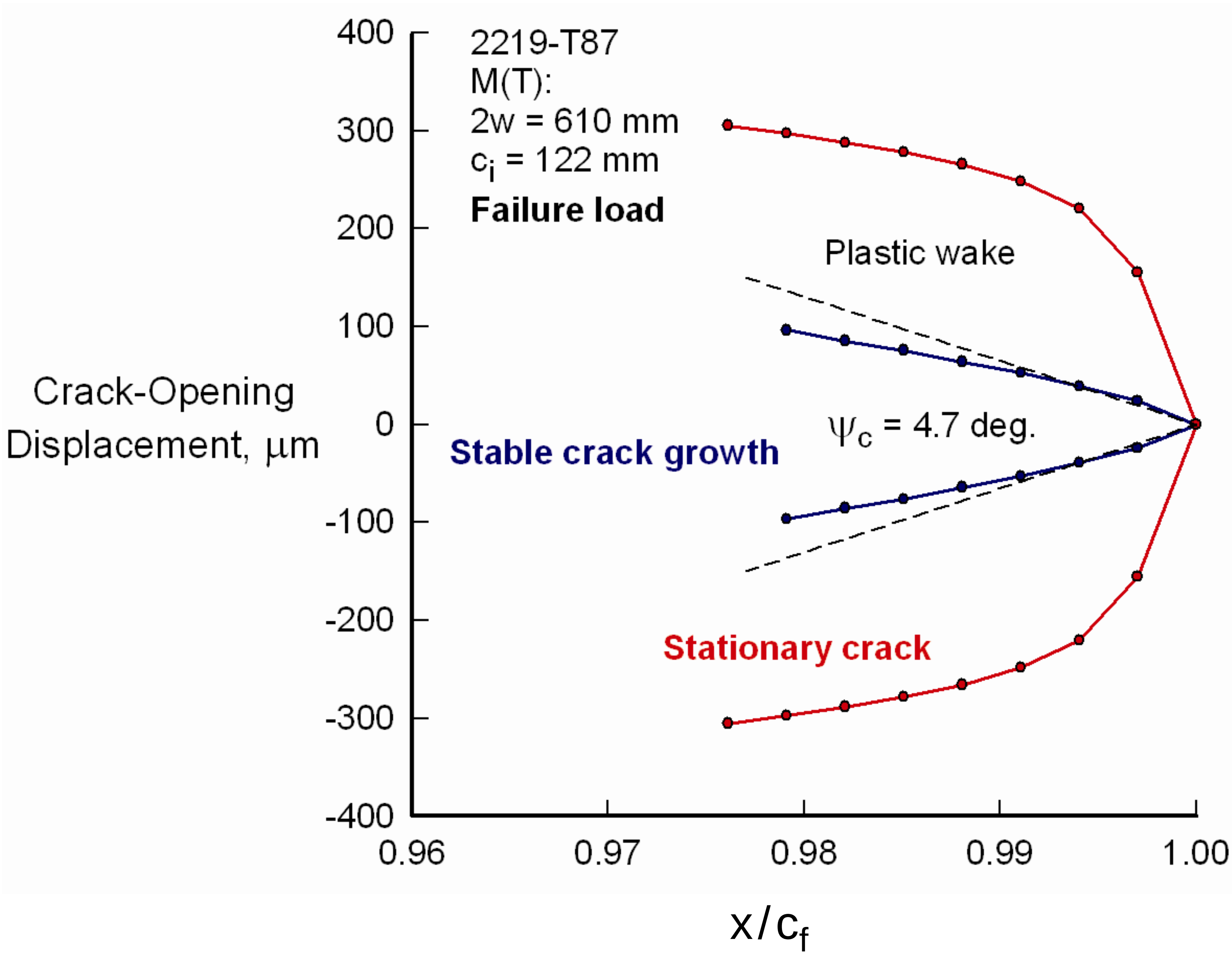
Crack-Opening Displacements for Stably Tearing Crack using Critical CTOA and Finite-Element Analyses



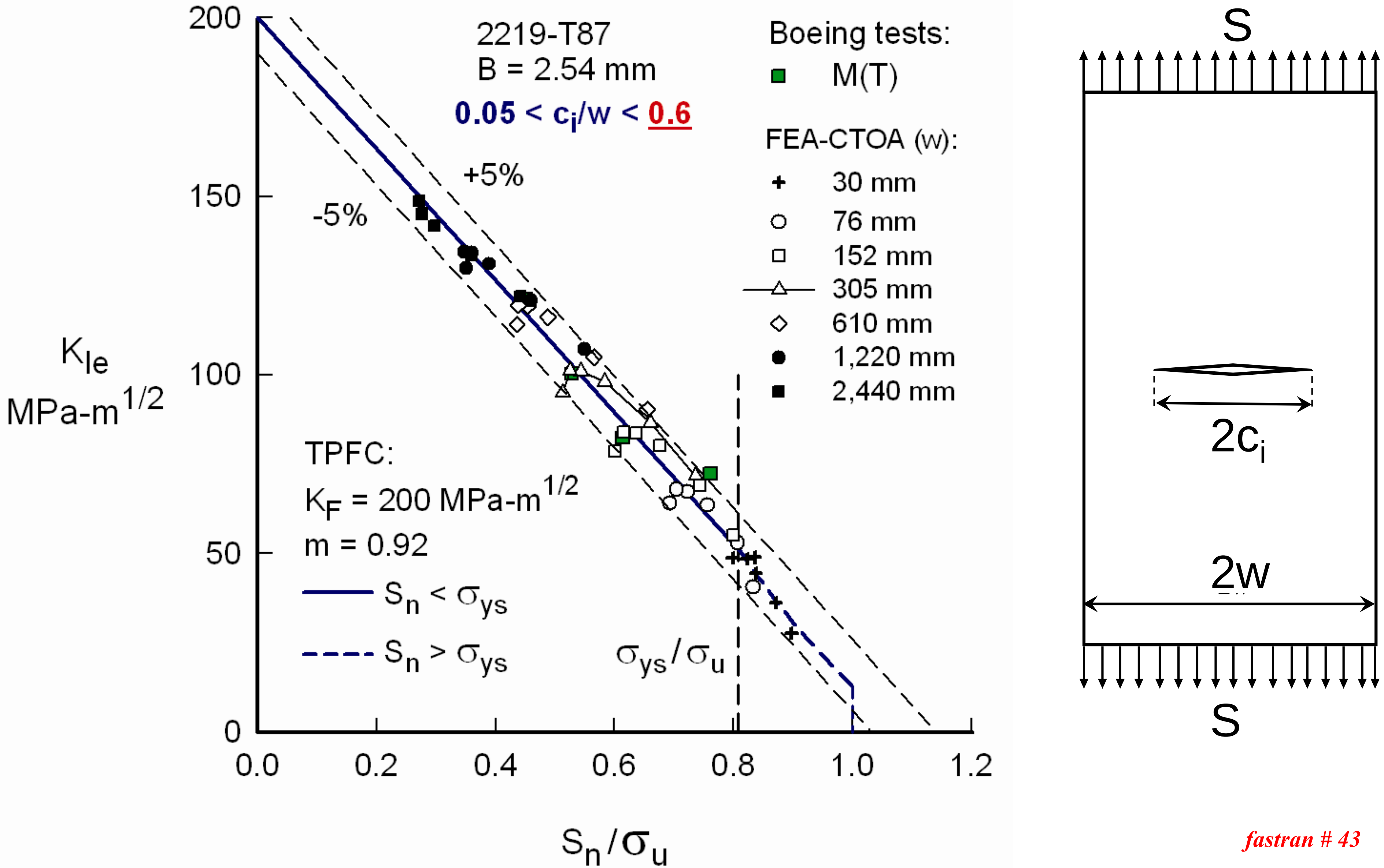


C.T. Sun
Purdue University
Mild steel

Crack-Opening Displacements for Stationary and Stably Tearing Crack using Critical CTOA-FEA Analyses



Elastic Stress-Intensity Factor at Failure for Wide Range of Middle-Crack Tension Specimens



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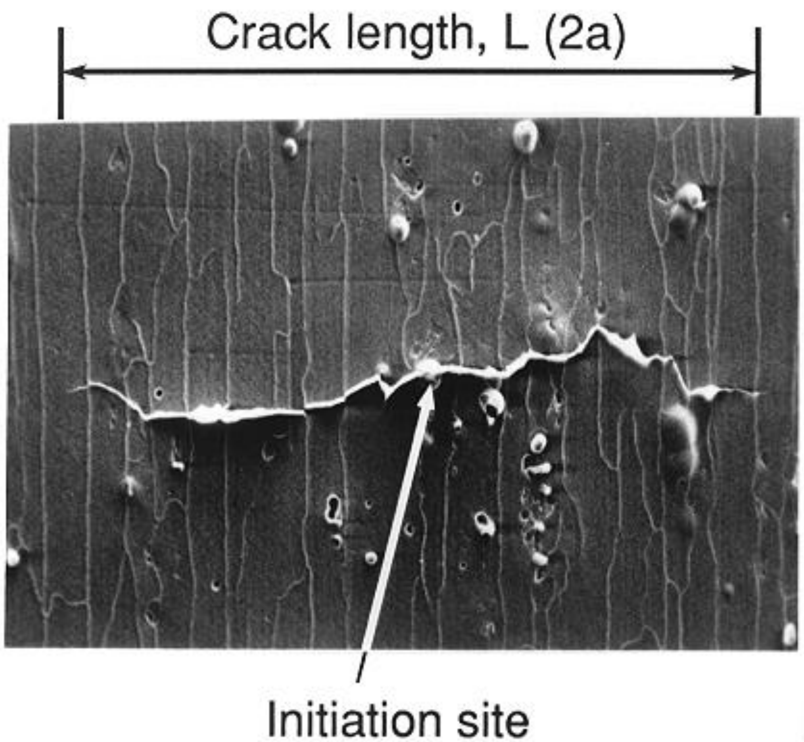
CRACK INITIATION AND SMALL-CRACK BEHAVIOR

- AGARD Structures and Materials Panel (1984-91) and NASA/CAE (1987-1994) Small-Crack Test and Analysis Programs

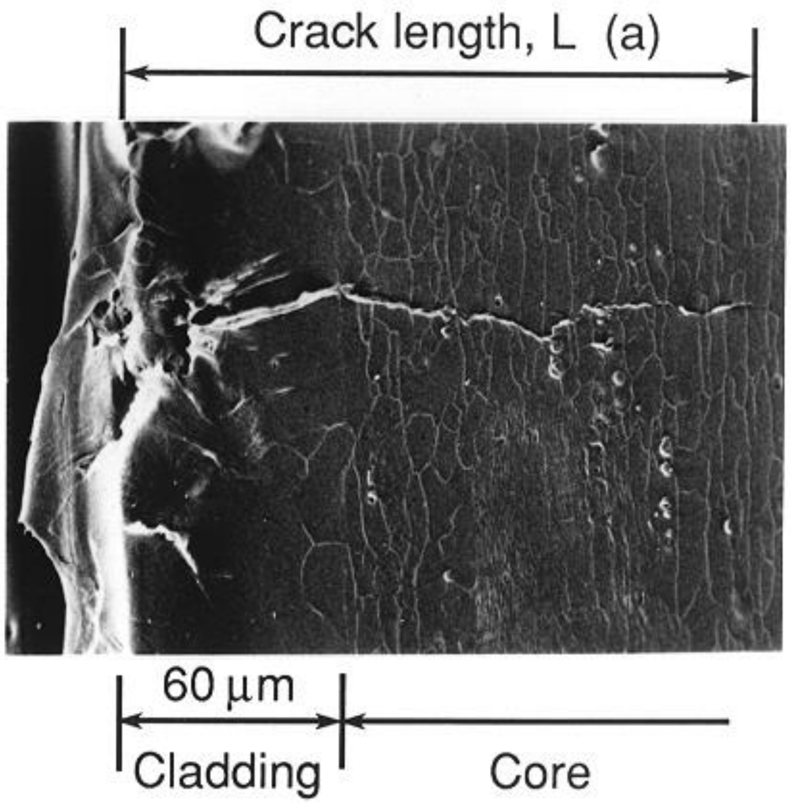
- Small- and Large-Crack Growth Rates

- DARPA SIPS Program (2003-2008)

SMALL-CRACK MEASUREMENTS IN ALUMINUM ALLOYS

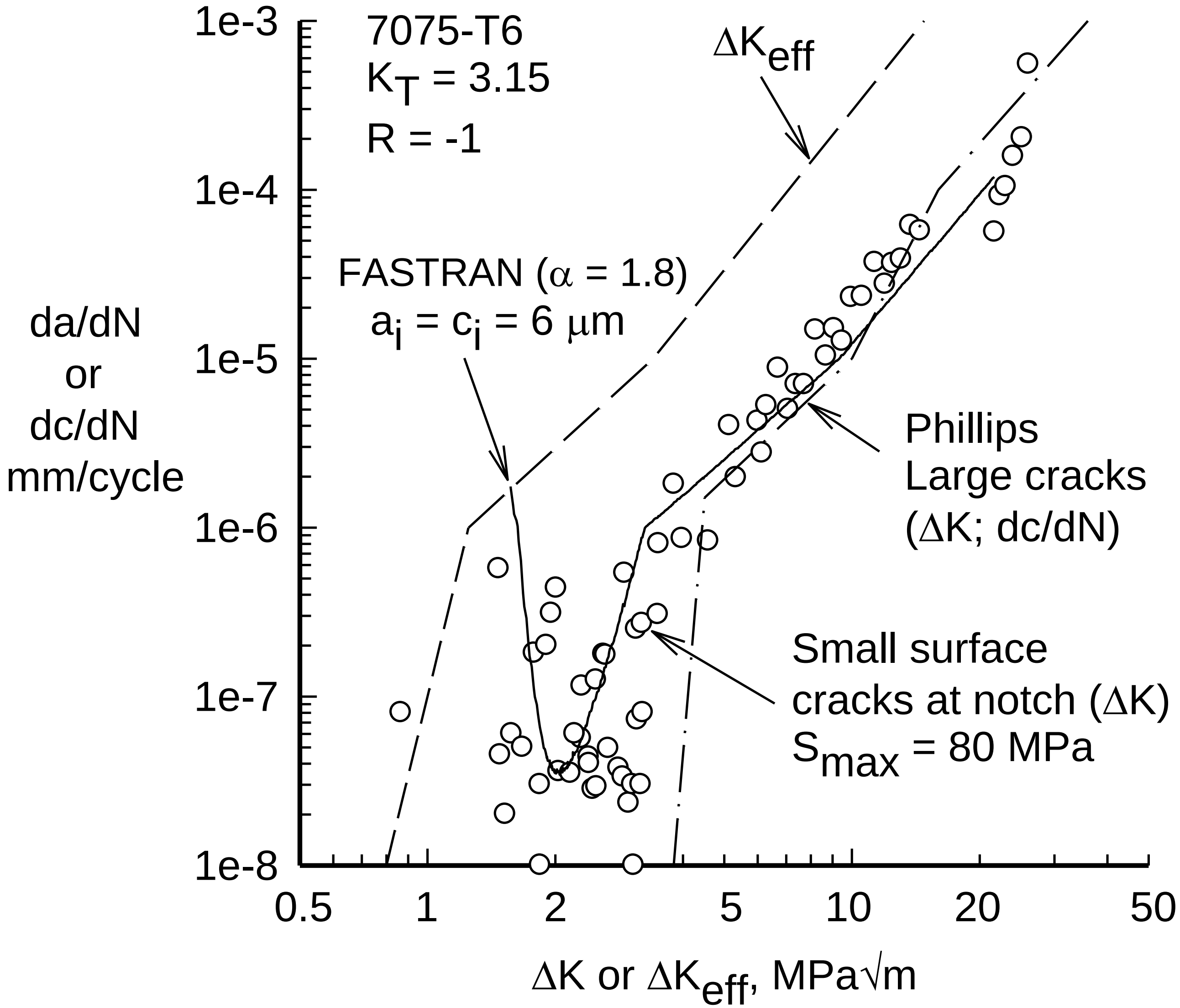


(a) 7075-T6

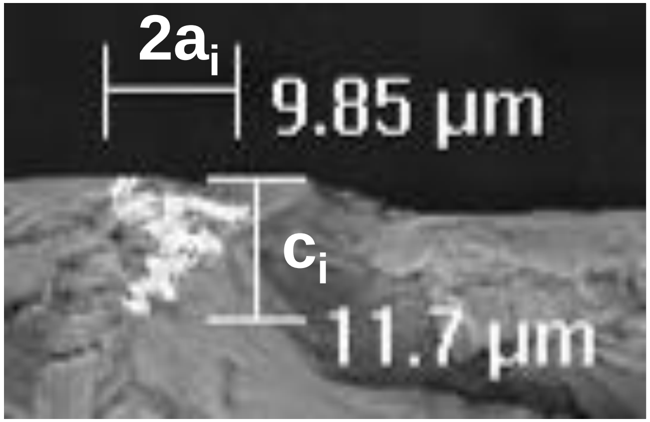


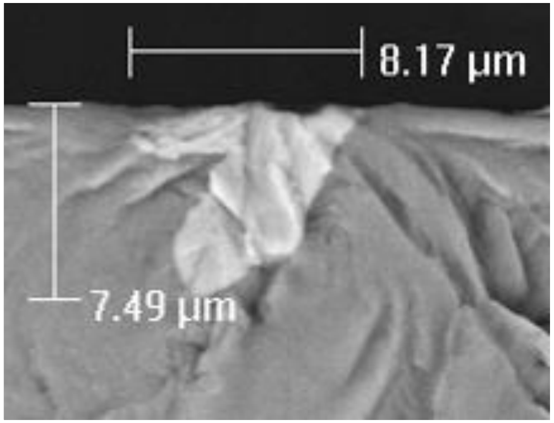
(b) Lc9CS (7075-T6 clad)

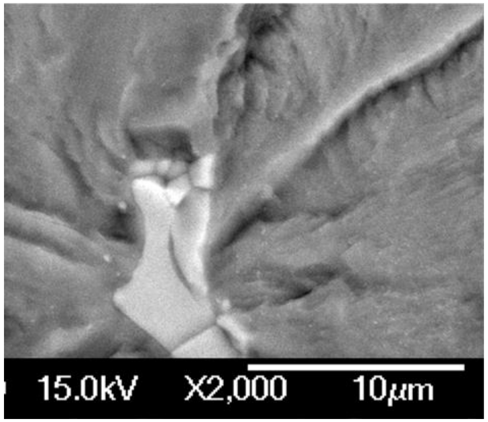
SMALL- AND LARGE-CRACK GROWTH RATES IN 7075-T6

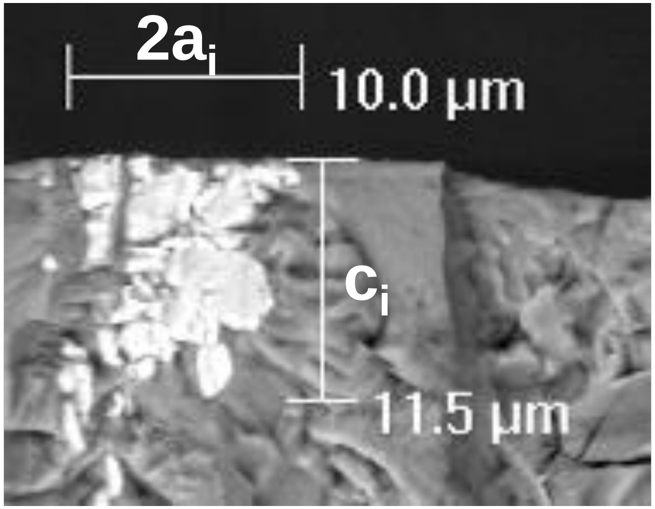


TYPICAL INITIATION SITES IN SIPS 7075-T651









Average flaw size:

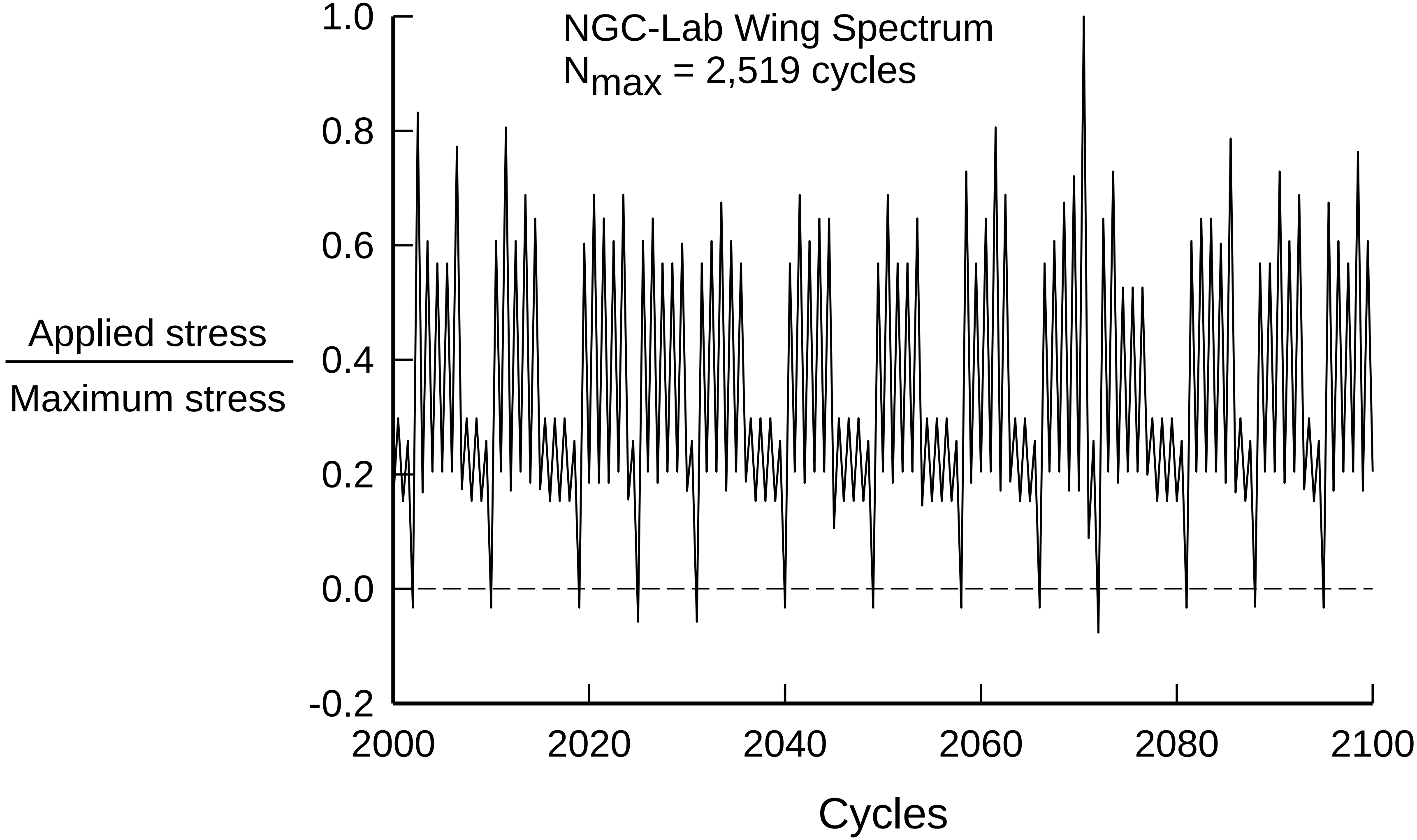
a_i = 4.3 µm (along bore)

c_i = 9.9 µm (depth from hole)

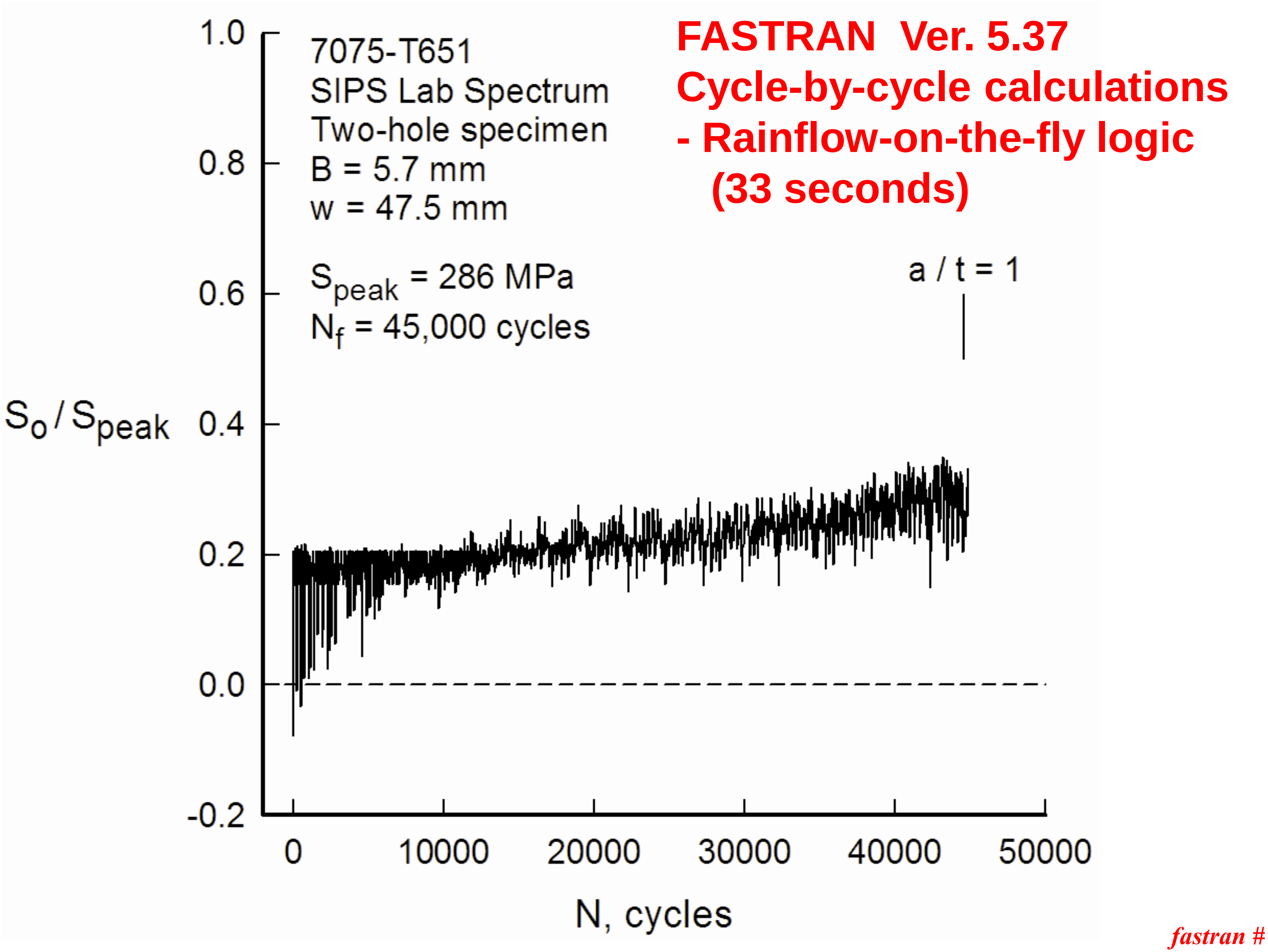
Semi-circular: 6.2 µm (equal area)

Not an EIFS, but RIFS – Real Initial Flaw Size

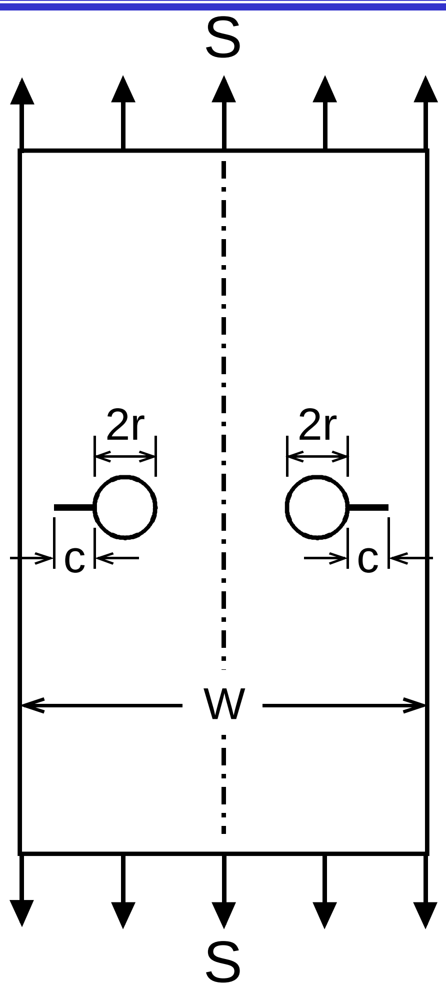
SIPS LABORATORY WING SPECTRUM



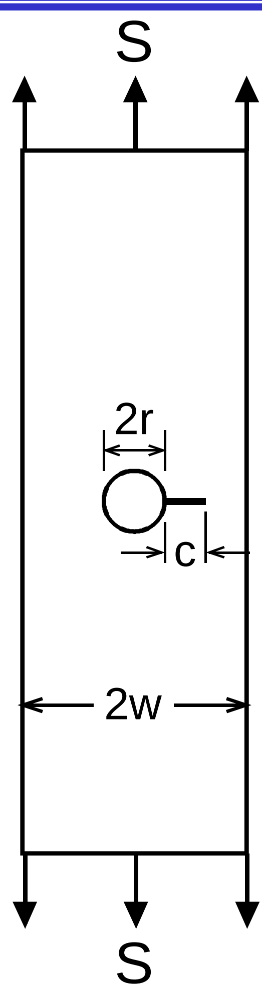
CALCULATED CRACK-OPENING STRESSES UNDER SIPS LABORATORY WING SPECTRUM LOADING



METHOD USED TO ANALYZE TWO-HOLE COUPONS

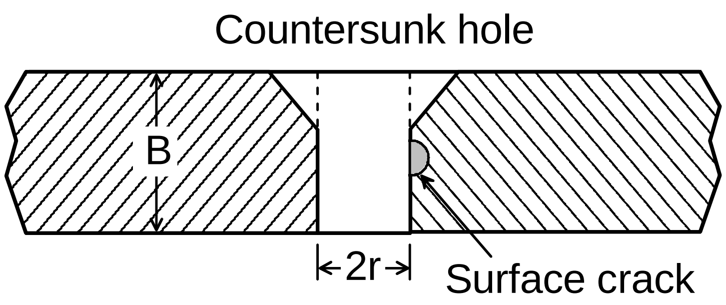


Two-hole coupon



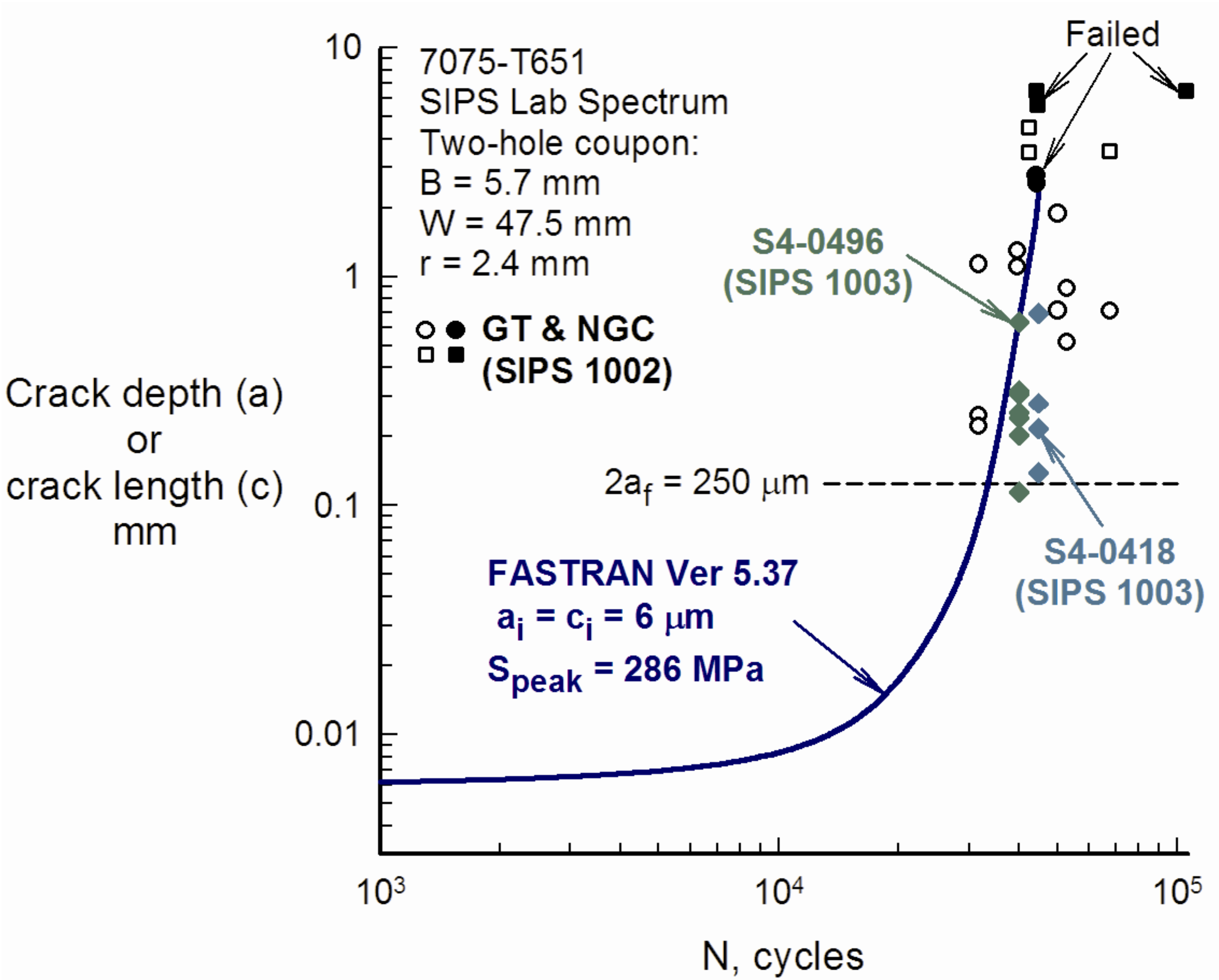
Modeled

Countersunk or straight-shank holes

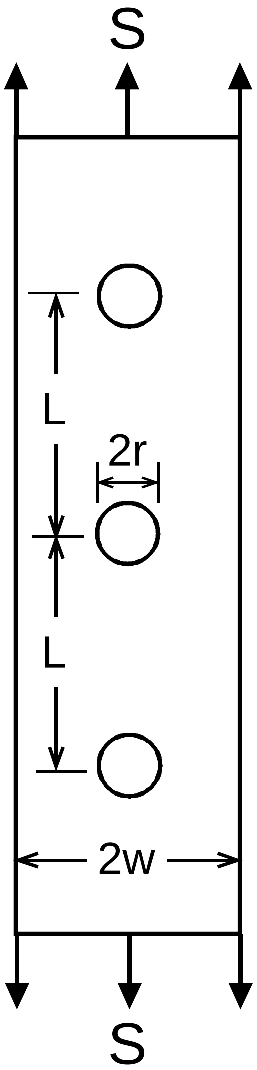


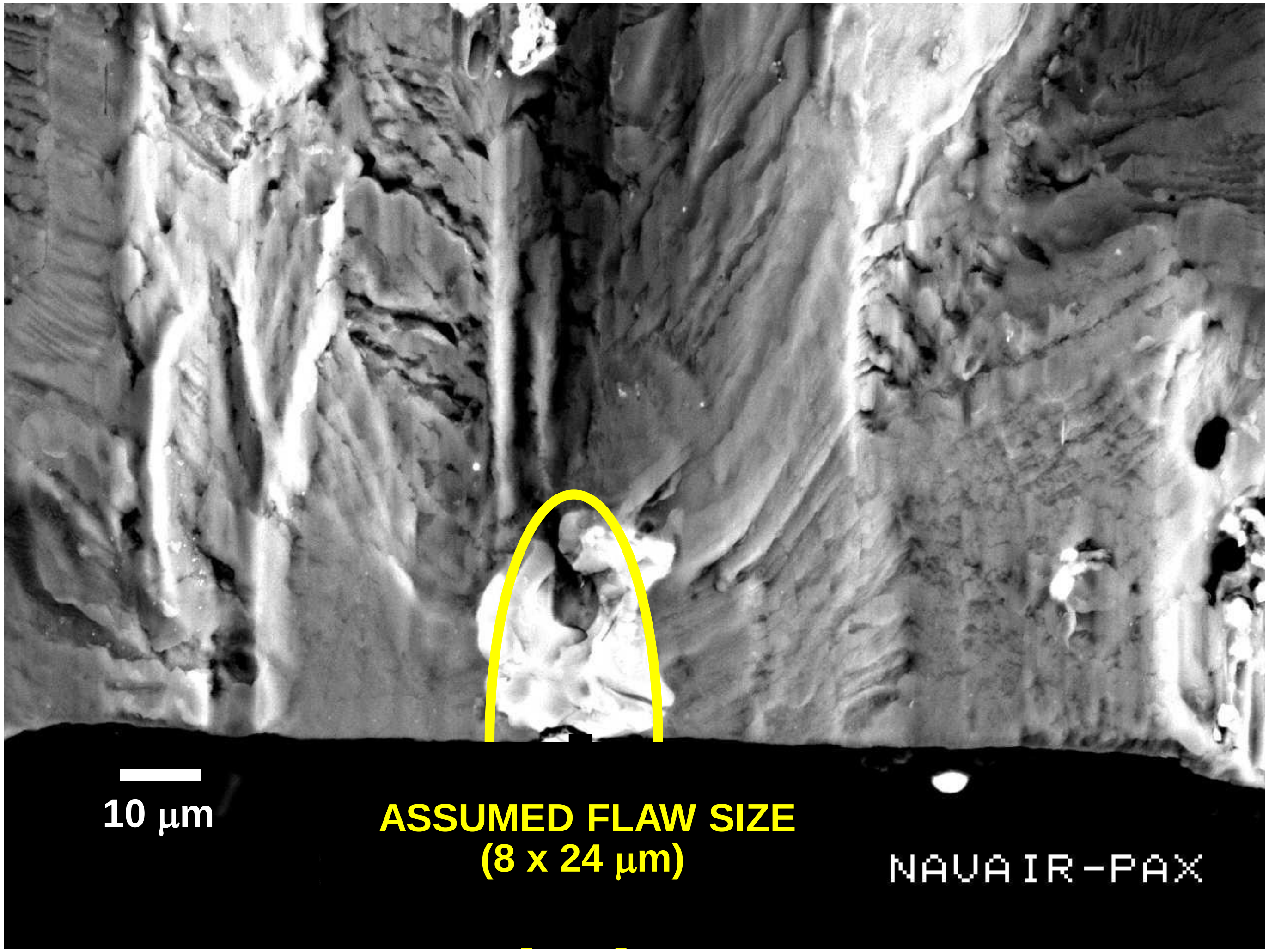
Initial flaw assumed to be a <u>surface crack</u> along hole bore and neglecting countersunk

MEASURED AND PREDICTED CRACK GROWTH UNDER SPECTRUM LOADING

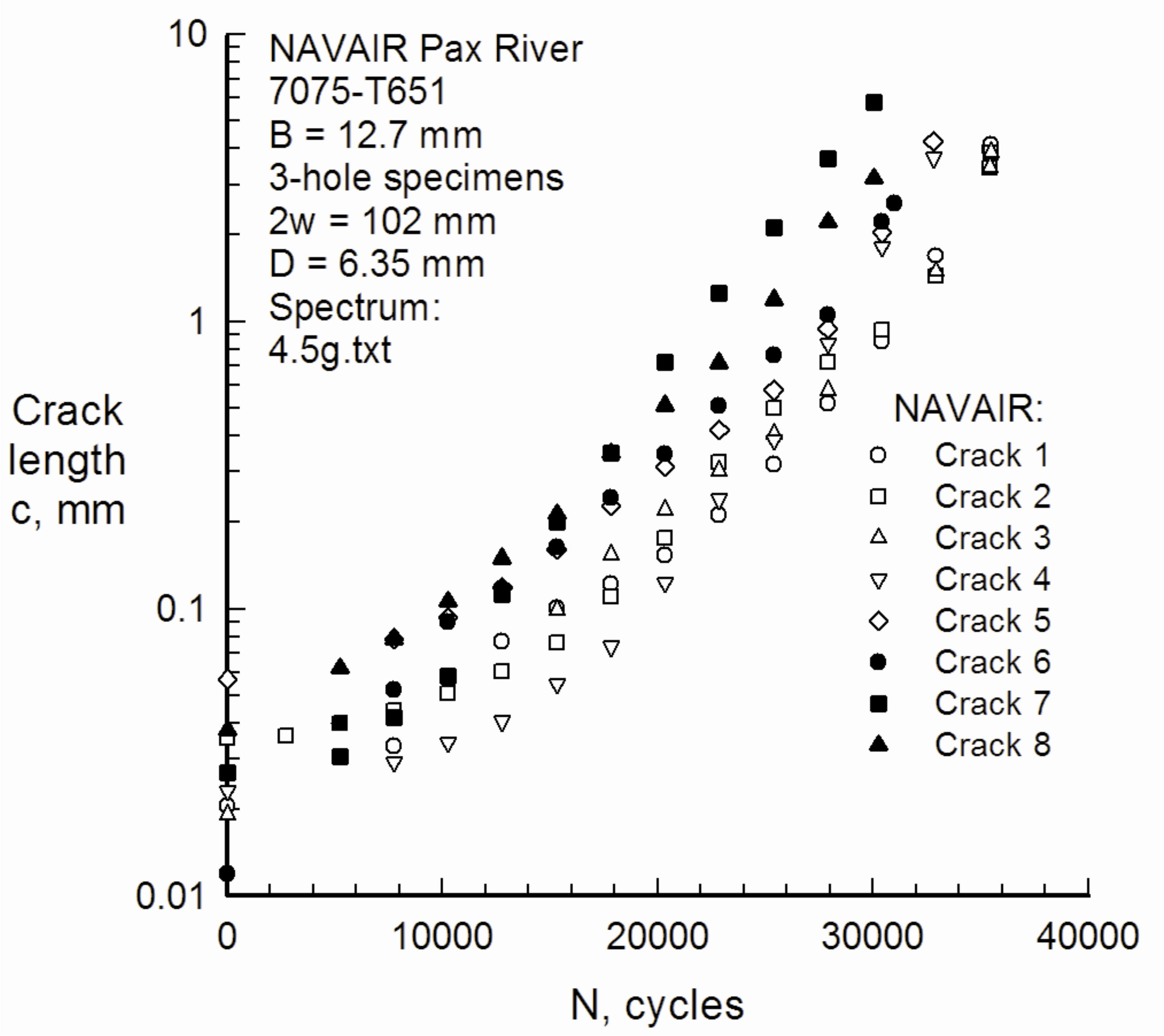


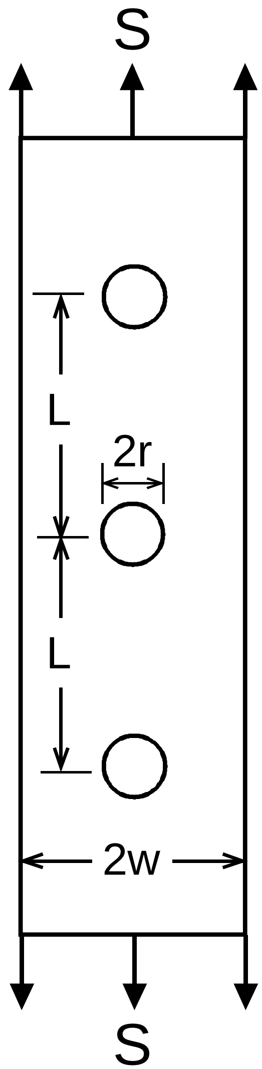
INITIATION SITE IN NAVAIR THREE-HOLE COUPON



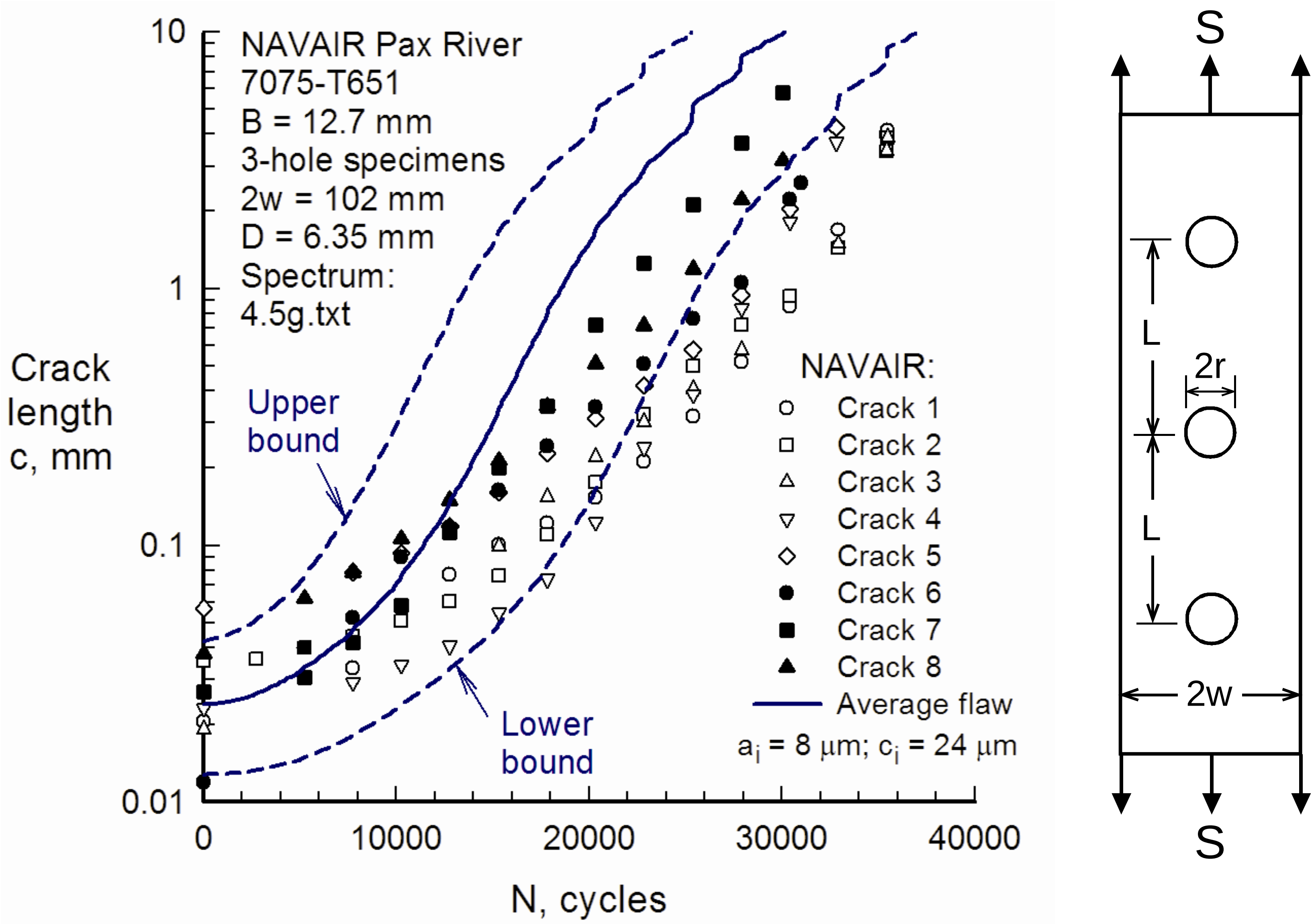


MEASURED CRACK GROWTH UNDER SPECTRUM LOADING ON NAVAIR TESTS





MEASURED AND PREDICTED CRACK GROWTH UNDER SPECTRUM LOADING ON NAVAIR TESTS



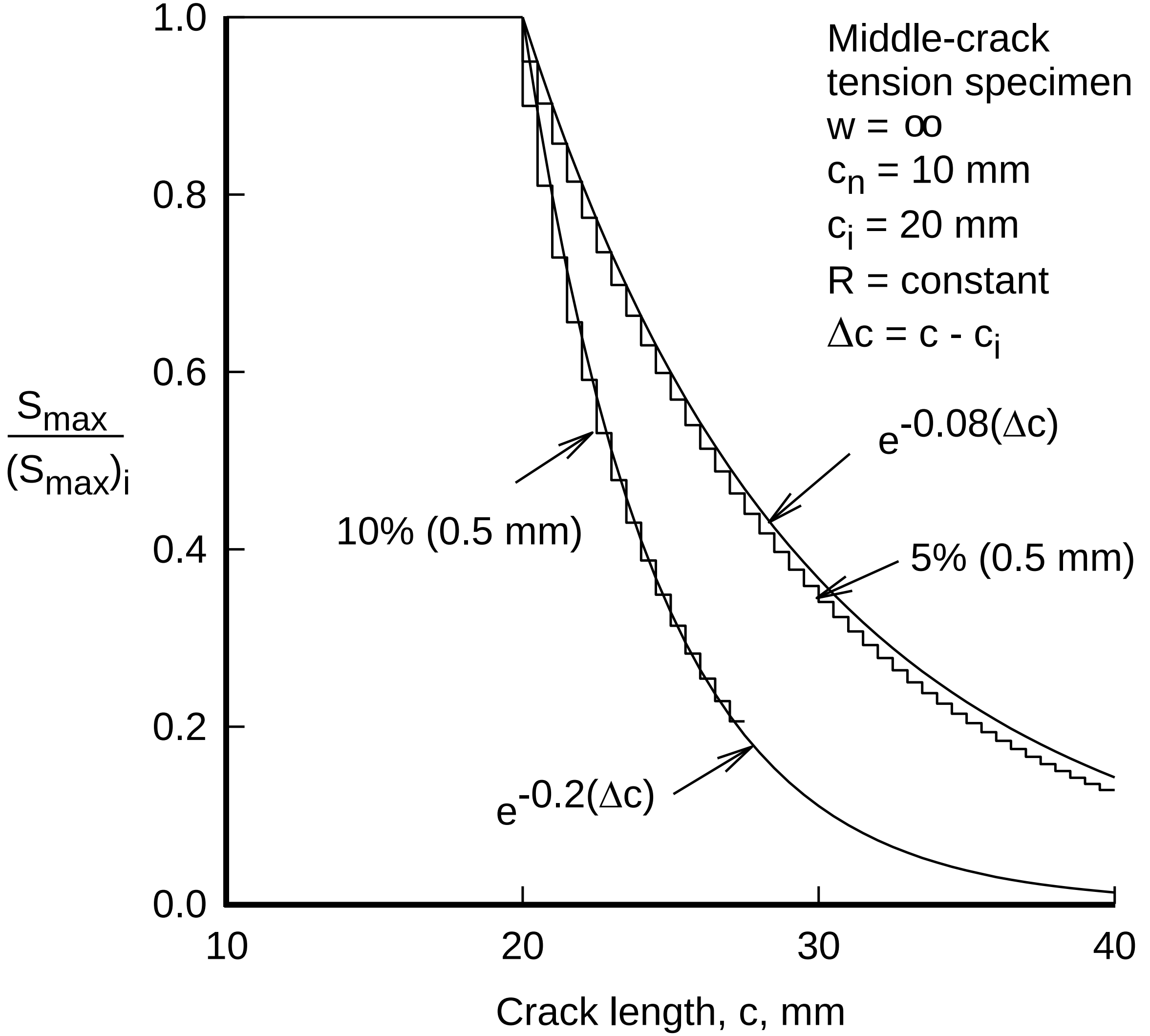
OUTLINE OF PRESENTATION

- Brief History on Fatigue-Crack Growth
- Plasticity-Induced Crack-Closure Model
- Crack Initiation and Small-Crack Behavior
- Fatigue-Crack Growth and Fracture
- Concluding Remarks

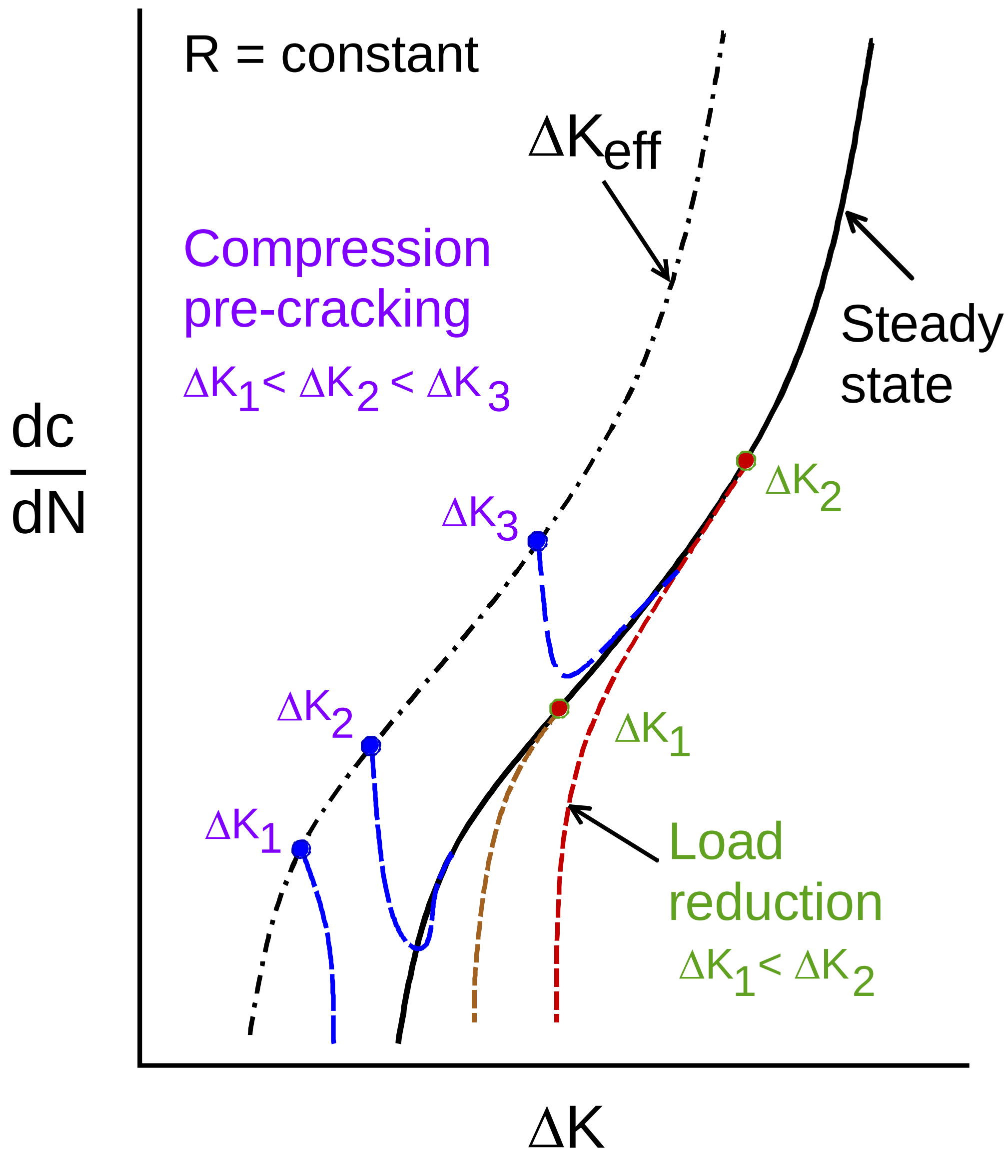
FATIGUE CRACK GROWTH

- **Thresholds for large cracks**
- **Cold-worked hole effects**
- **Spectrum loading effects**

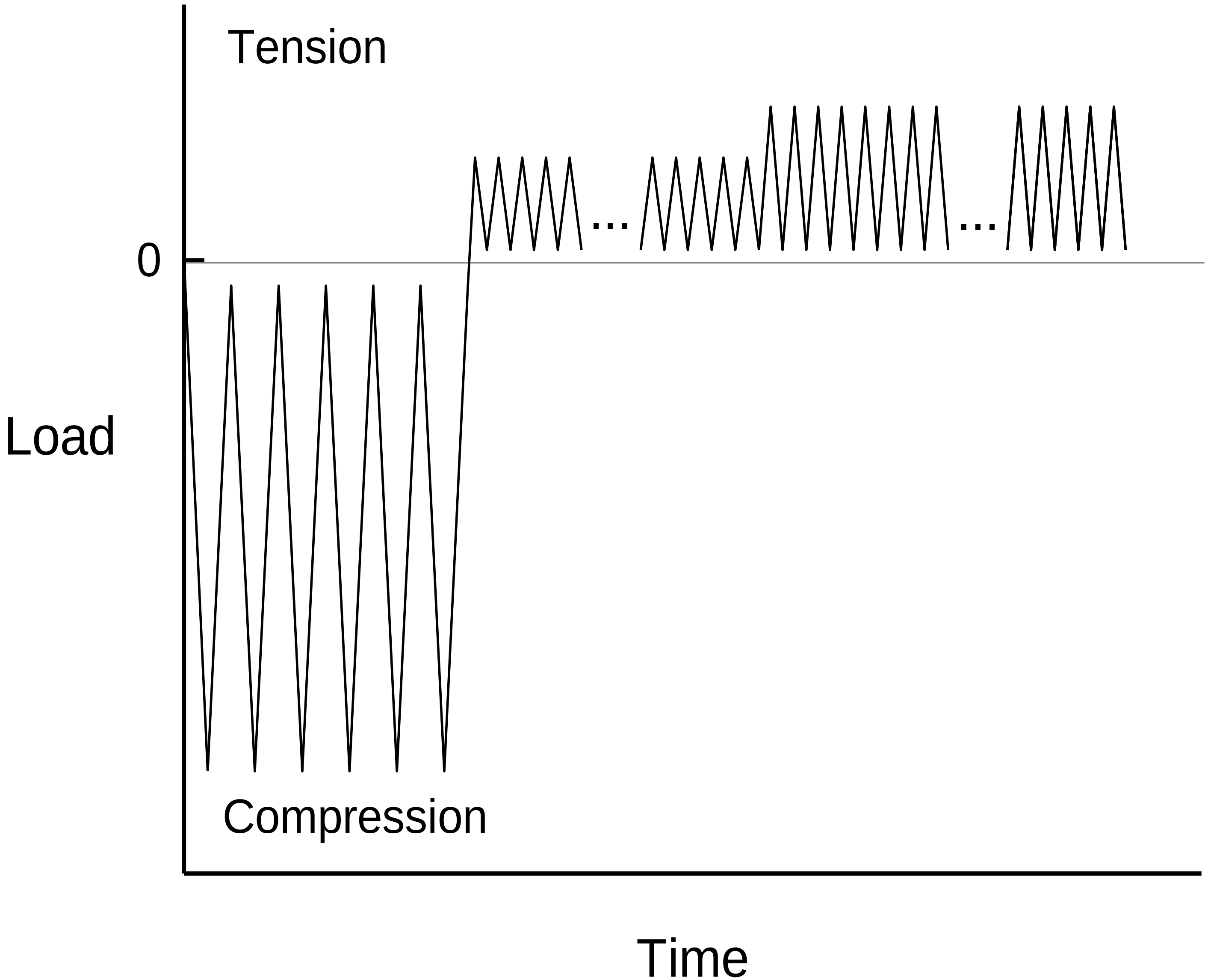
ASTM LOAD-REDUCTION PROCEDURES



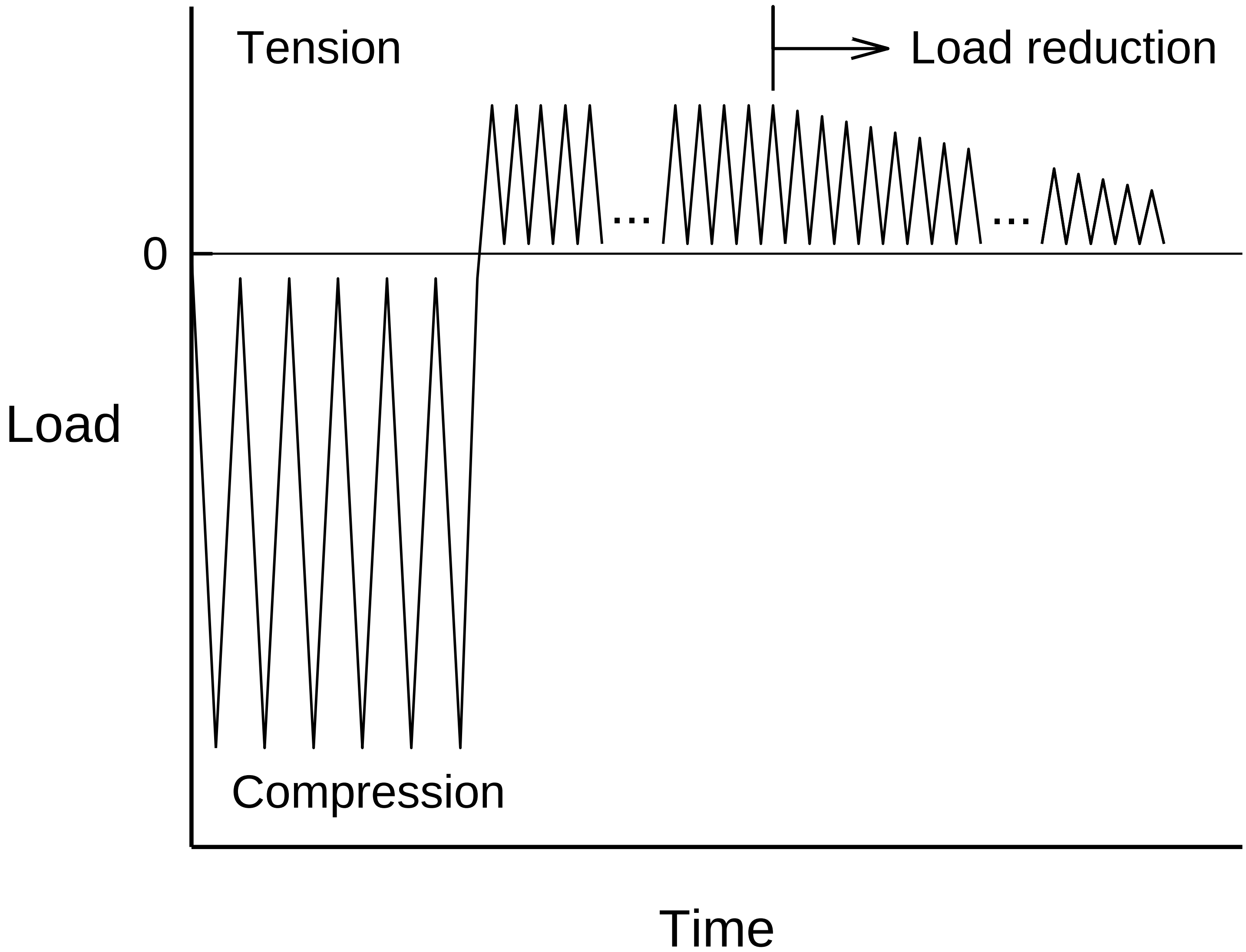
TYPICAL BEHAVIOR FOR LOAD-REDUCTION AND COMPRESSION PRE-CRACKING THRESHOLD TESTING



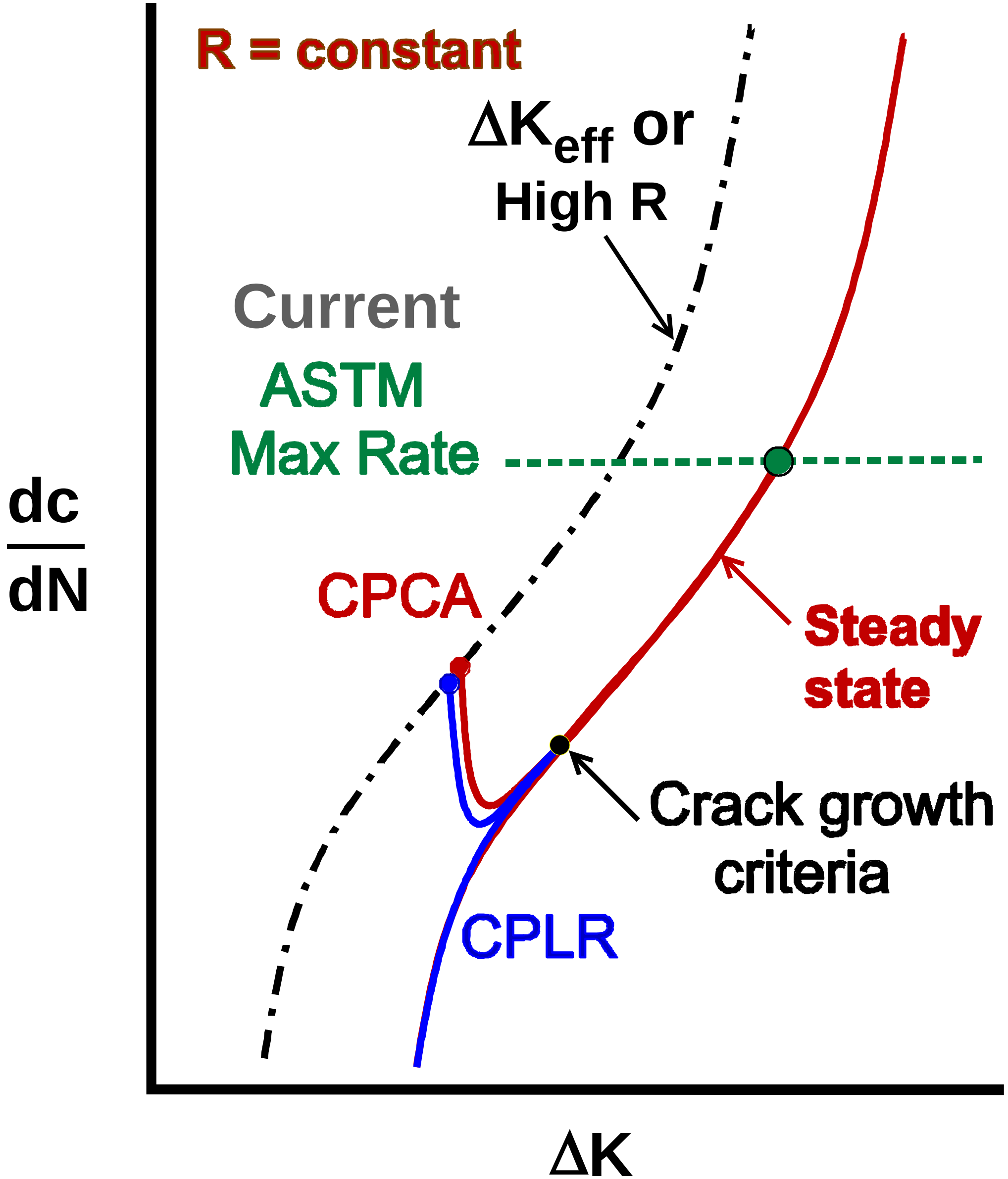
COMPRESSION-COMPRESION PRECRACKING AND CONSTANT-AMPLITUDE (CPCA) LOAD TESTING



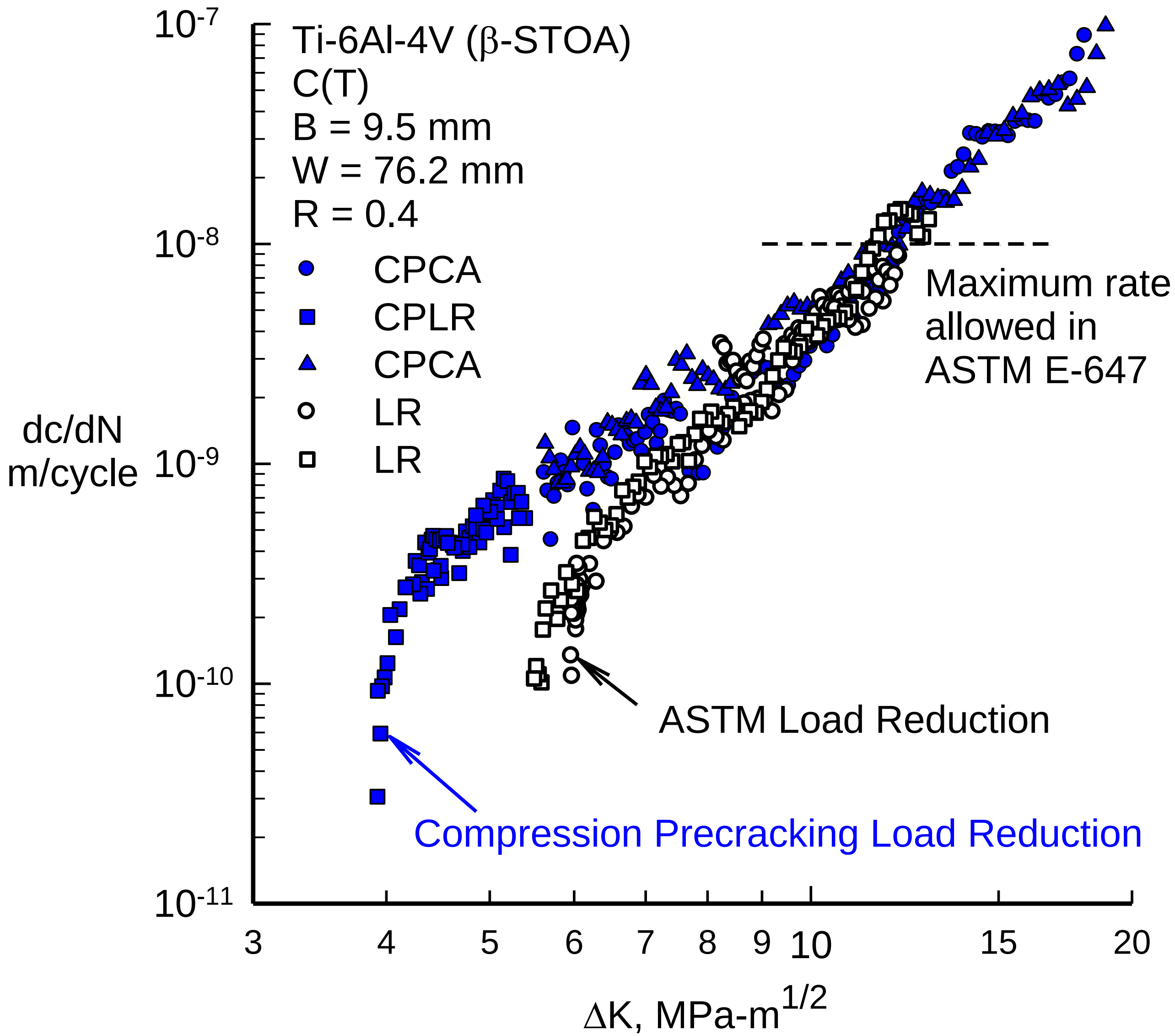
COMPRESSION-COMPRESION PRECRACKING AND LOAD-REDUCTION (CPLR) THRESHOLD TESTING



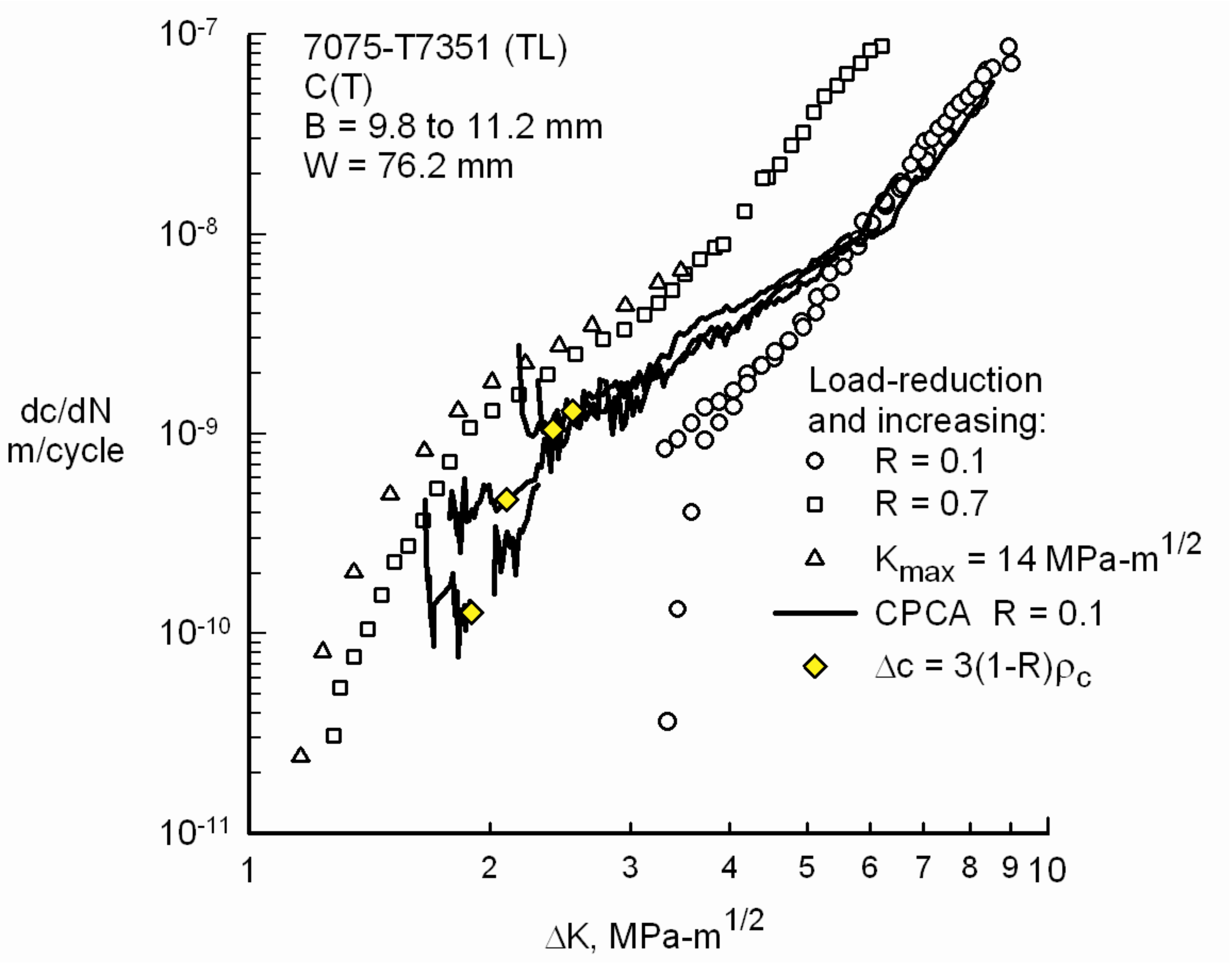
METHODS TO GENERATE STEADY-STATE DATA



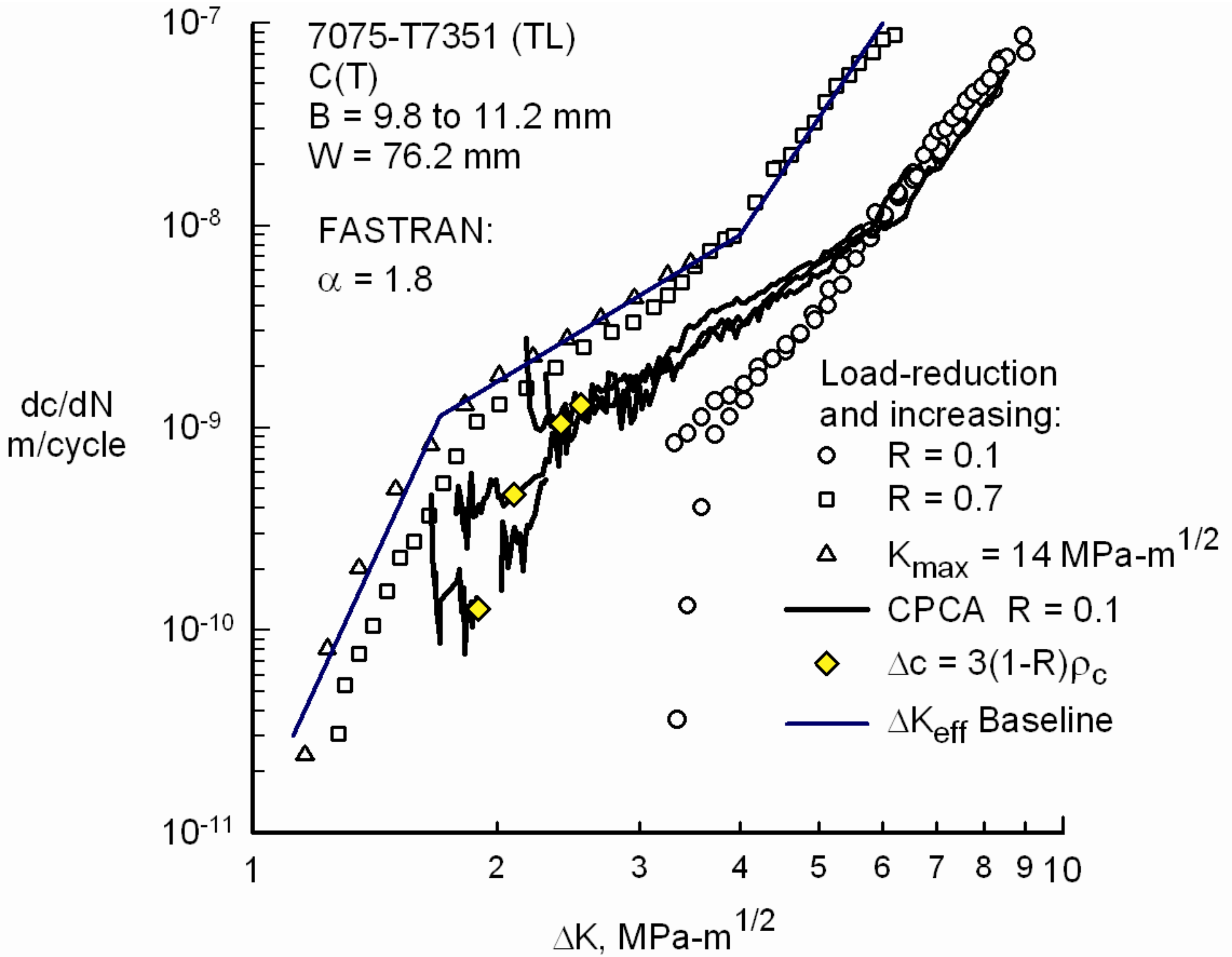
CPCA AND LOAD-REDUCTION TESTING AT MEDIUM STRESS RATIO ON TITANIUM β-STOA ALLOY



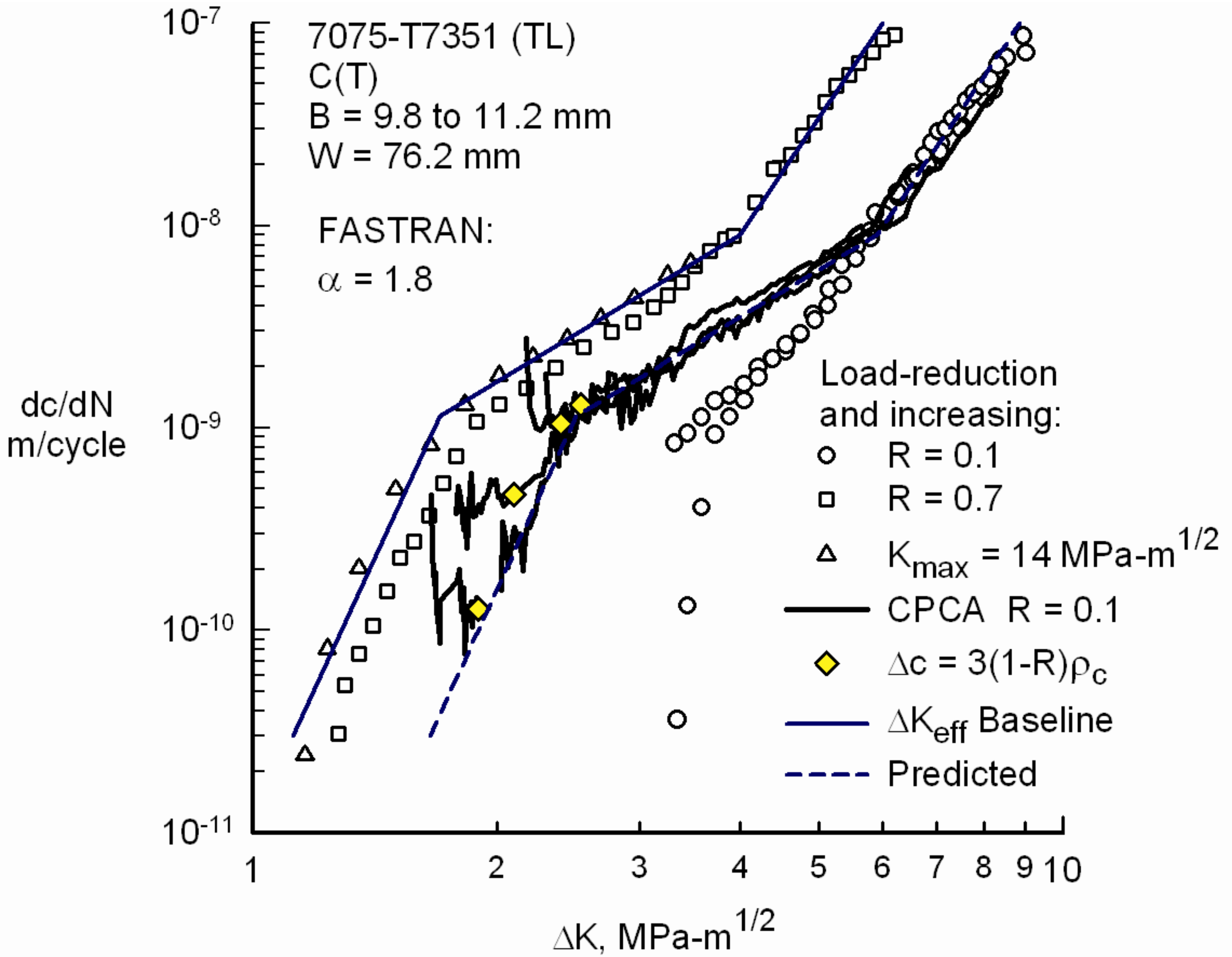
CPCA AND LOAD-REDUCTION THRESHOLD TESTING ON 7075-T7351 AT R = 0.1 CONDITIONS



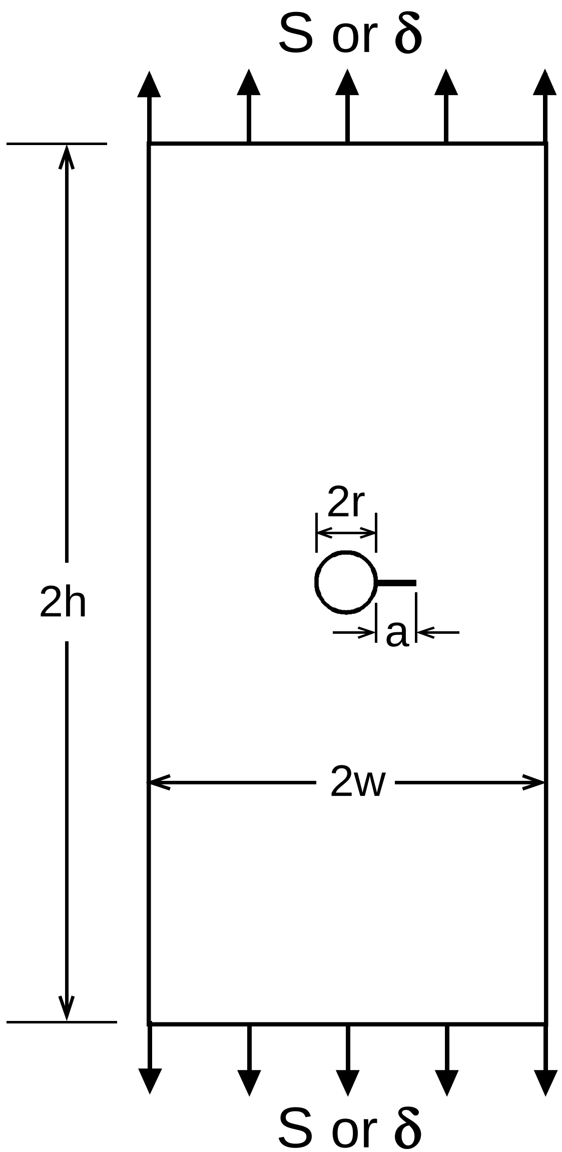
CPCA AND LOAD-REDUCTION THRESHOLD TESTING ON 7075-T7351 AT R = 0.1 CONDITIONS



CPCA AND LOAD-REDUCTION THRESHOLD TESTING ON 7075-T7351 AT R = 0.4 CONDITIONS



COLD-WORKED HOLE TEST SPECIMEN



Test procedure:

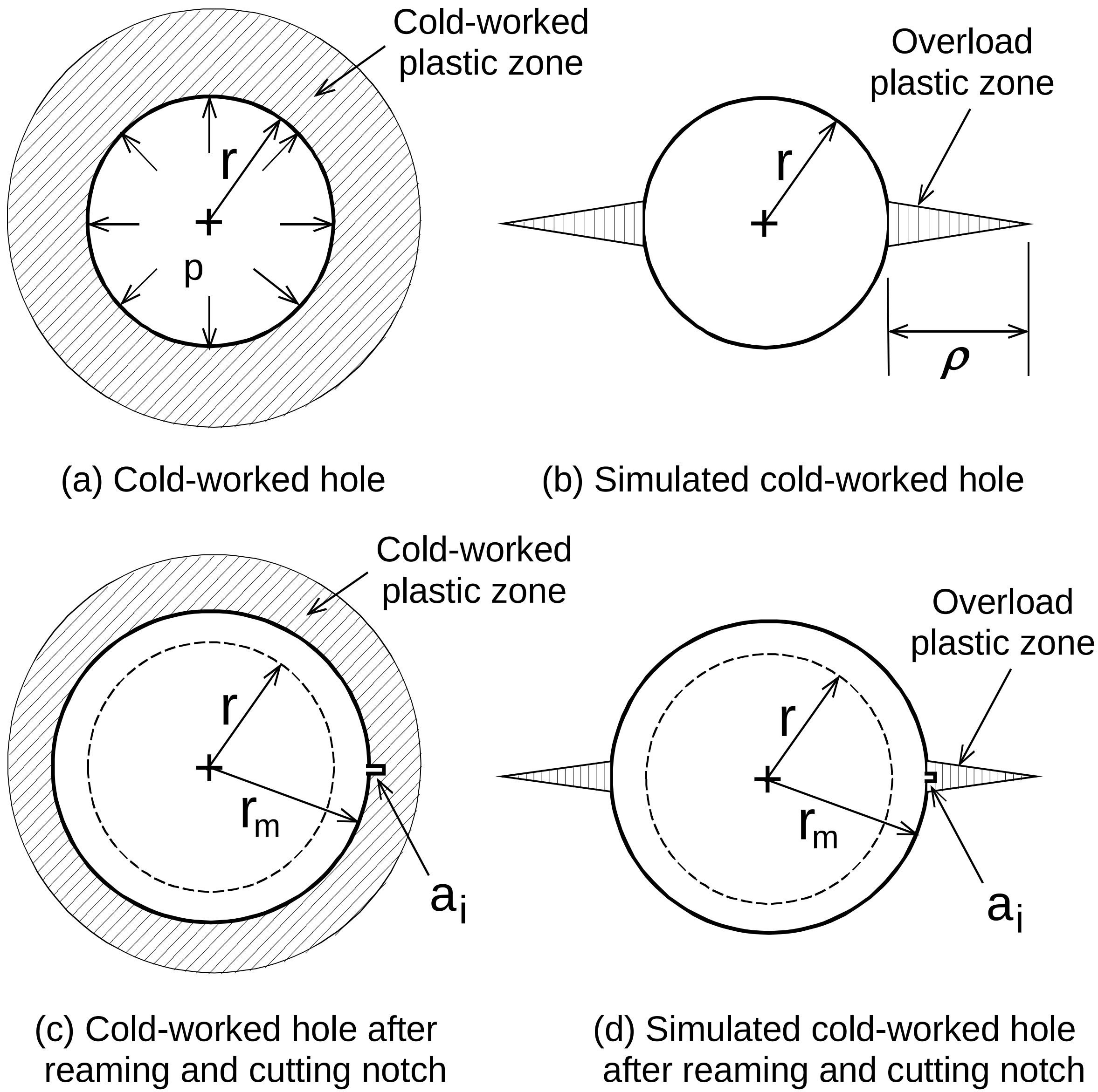
<u>Sikorsky:</u>

(1) Holes drilled
(2) Cold-worked (4.5%)
(3) Reamed
(4) EDM Notched

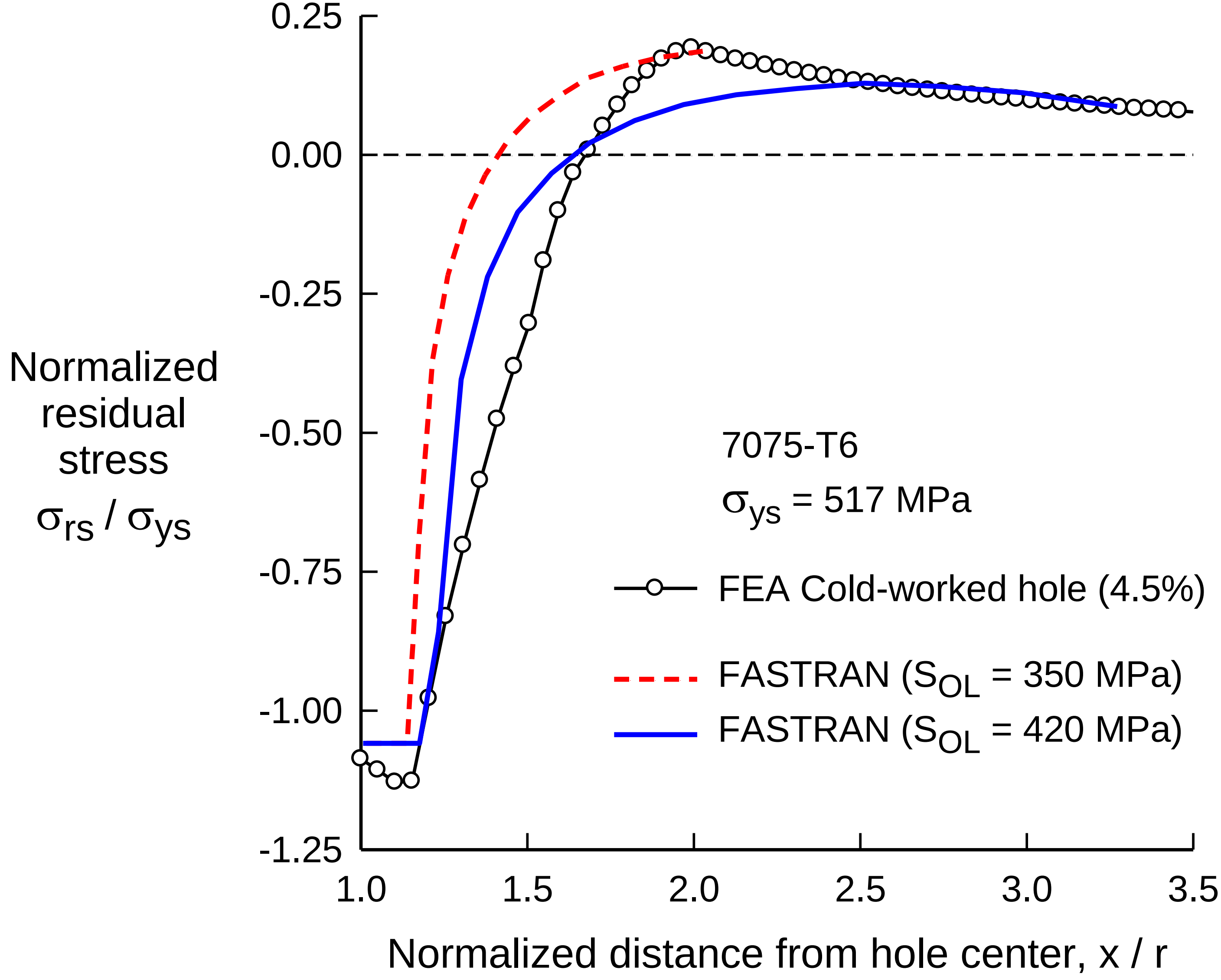
<u>Tested at MSU:</u>

(5) Constant-amplitude loading

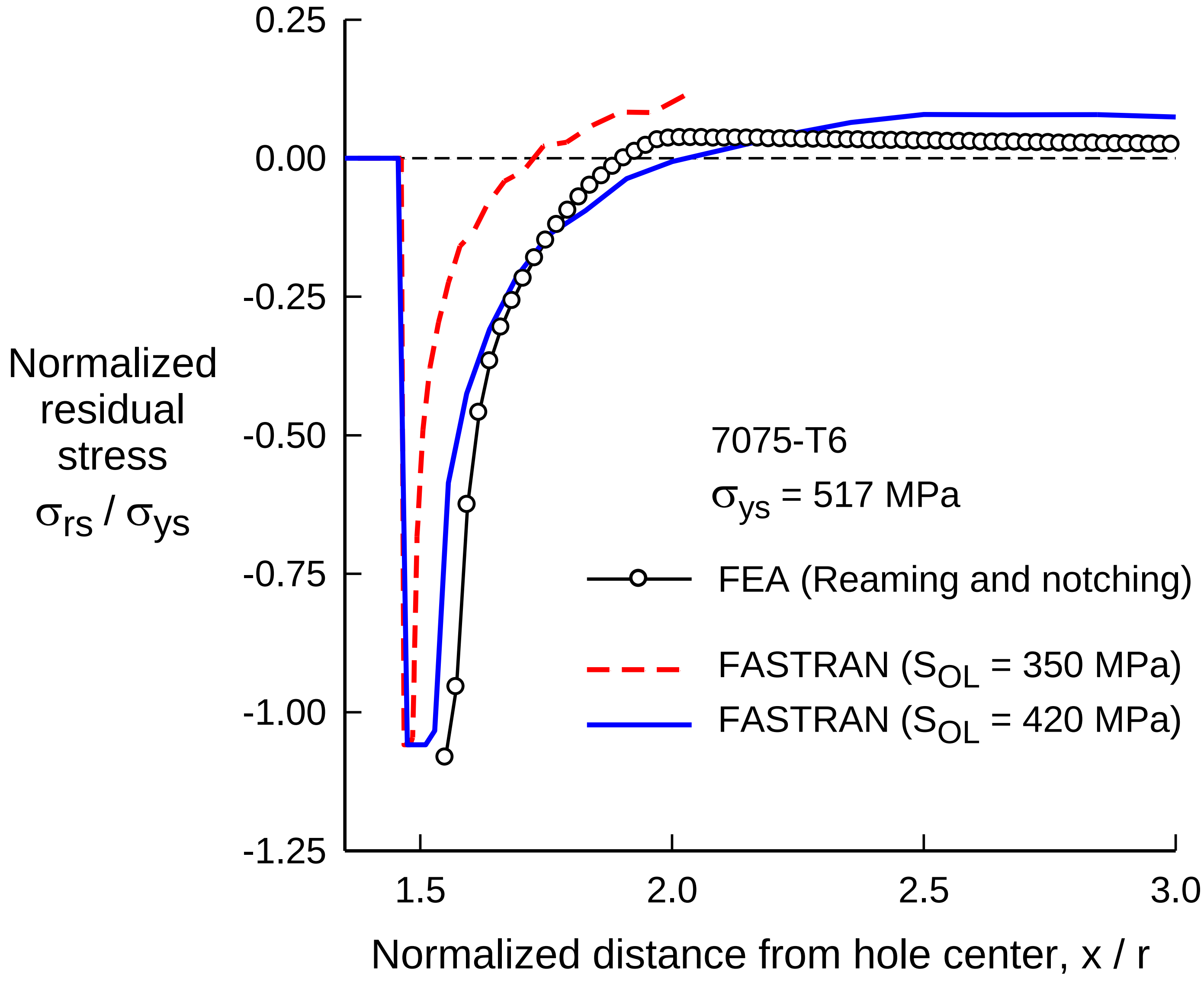
SIMULATION OF COLD-WORKING AND NOTCHING



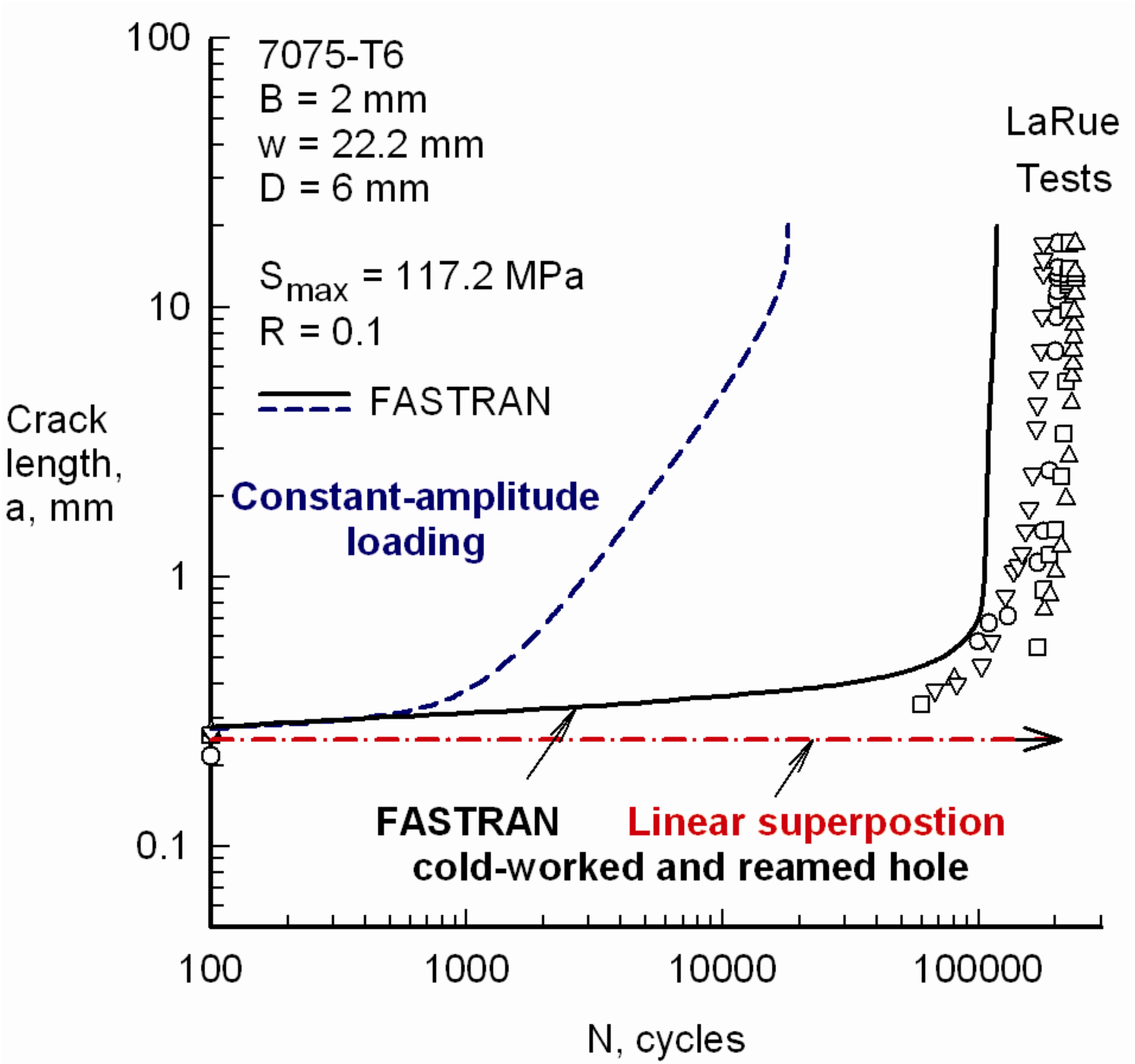
RESIDUAL STRESSES AFTER COLD-WORKING



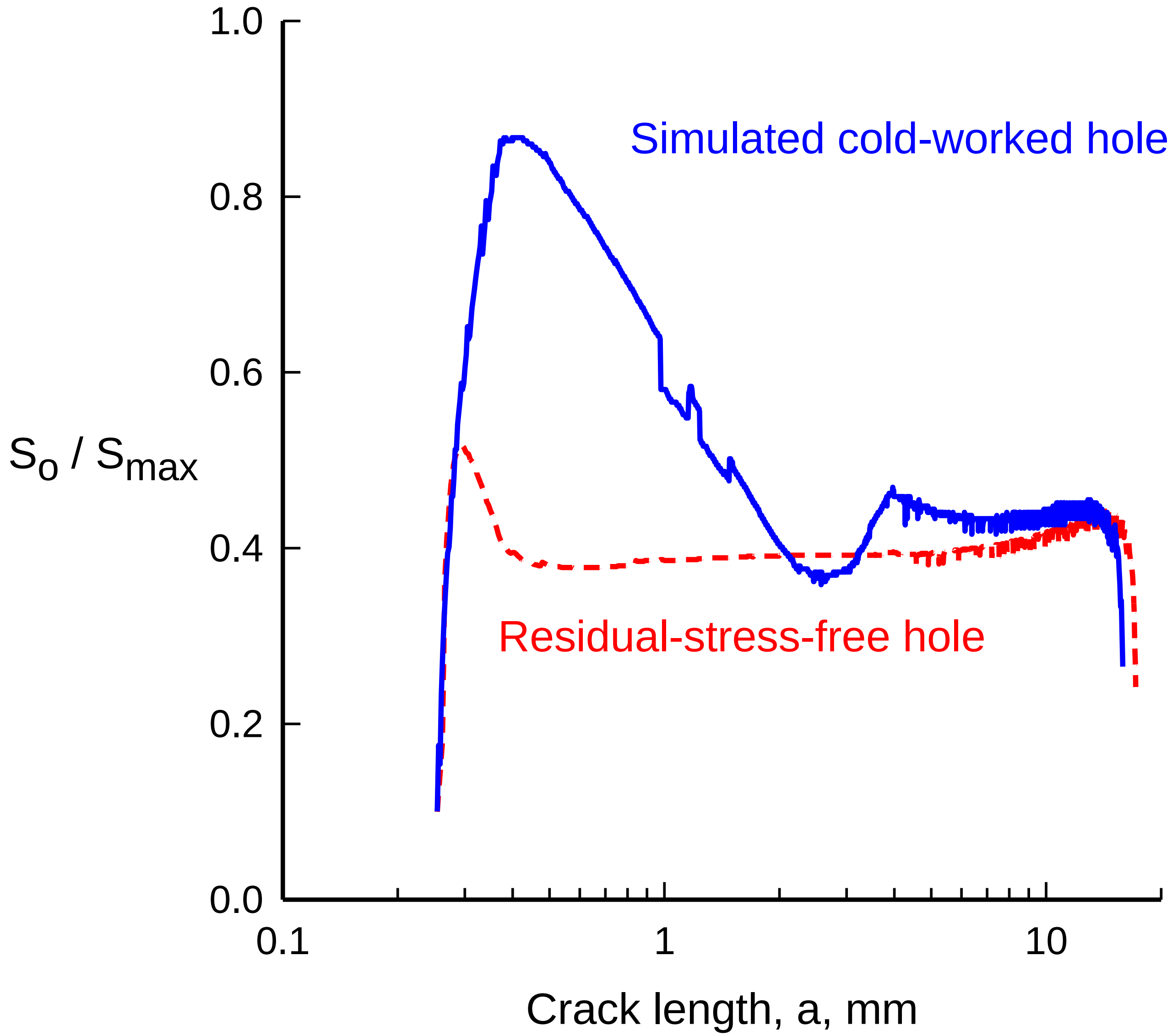
RESIDUAL STRESSES AFTER COLD-WORKING, REAMING AND NOTCHING



MEASURED AND PREDICTED CRACKING BEHAVIOR ON COLD-WORKING HOLE SPECIMENS



CALCULATED CRACK-OPENING STRESSES FOR CRACK GROWTH WITH OR WITHOUT COLD-WORKED HOLE



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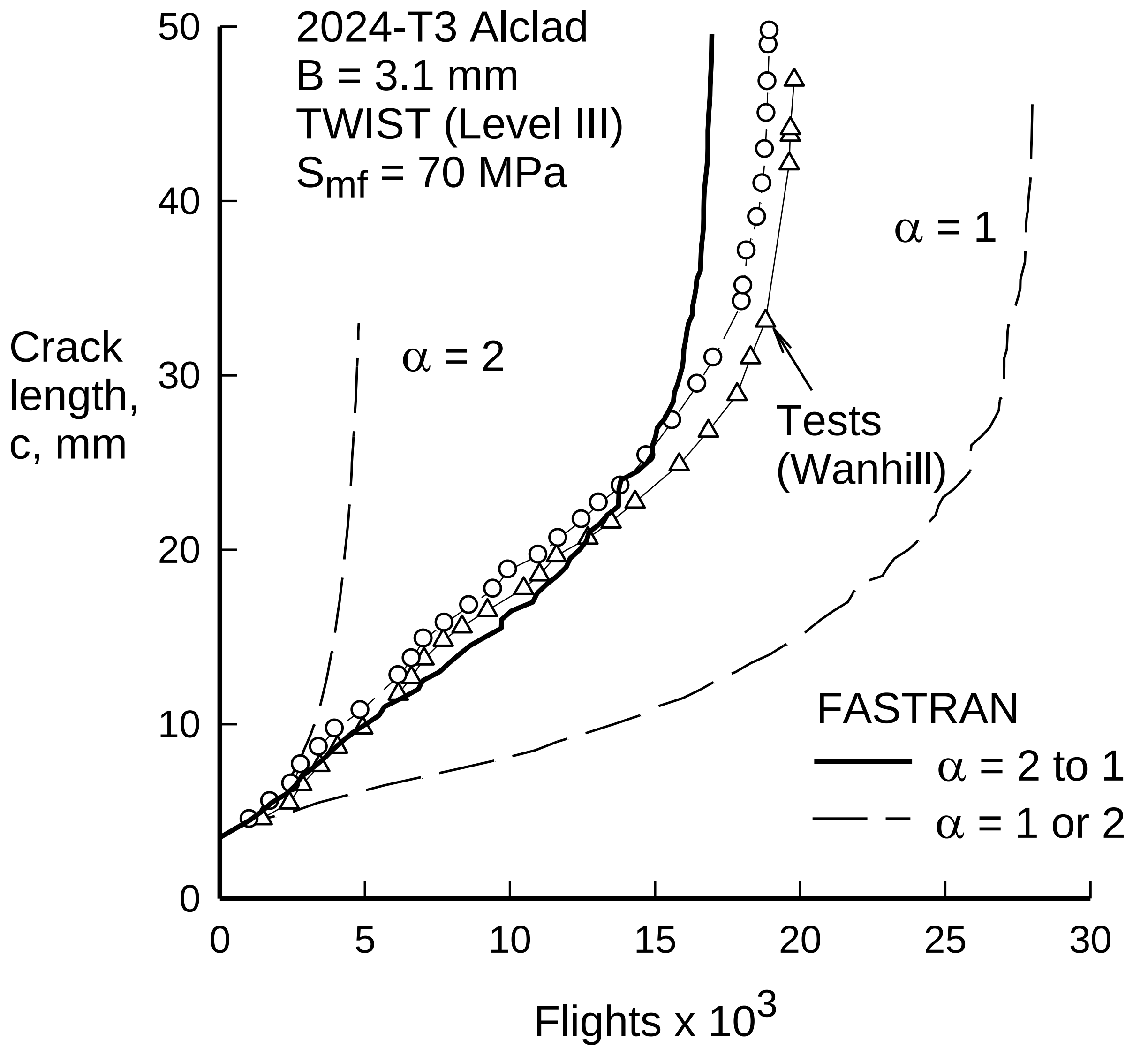
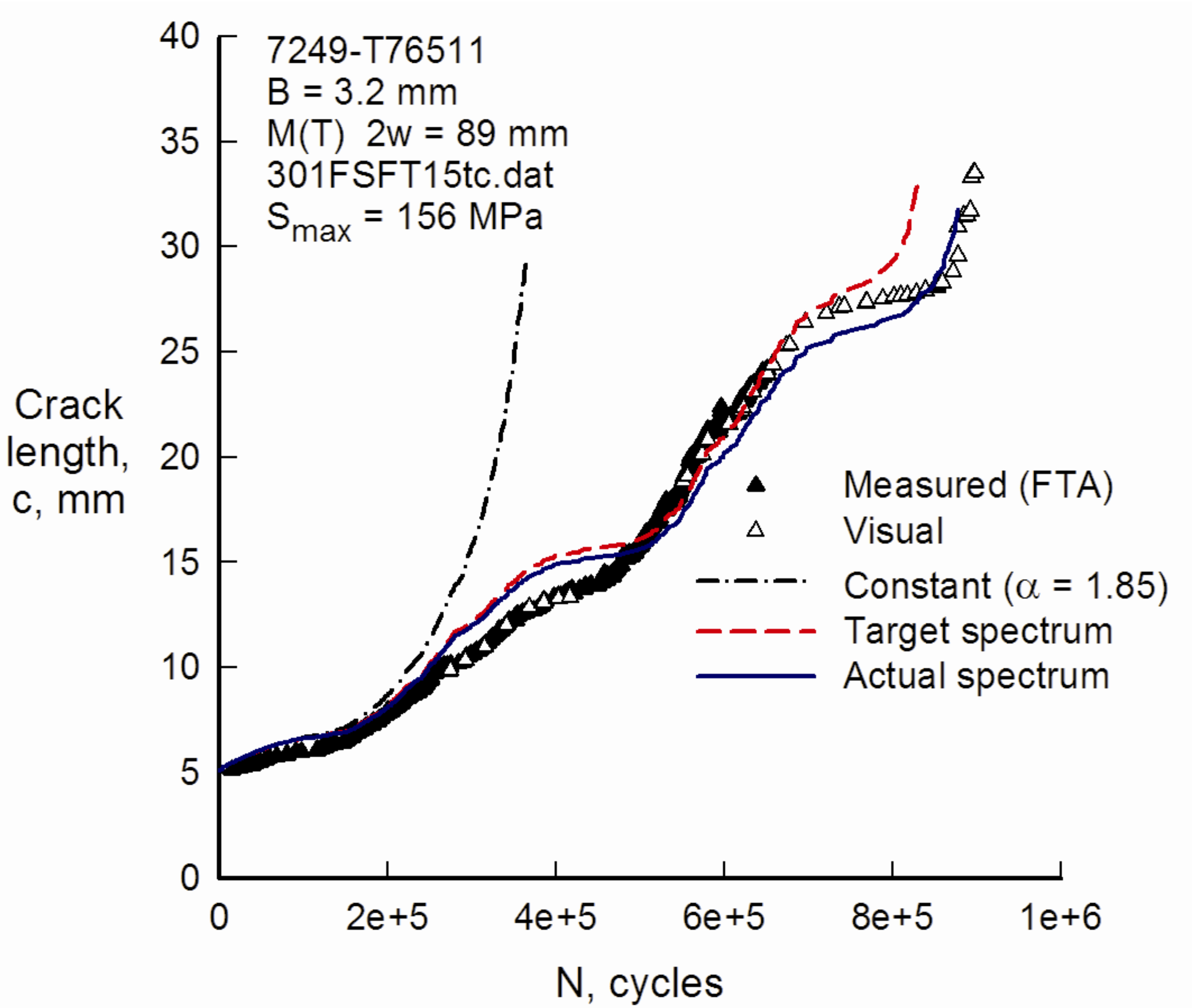
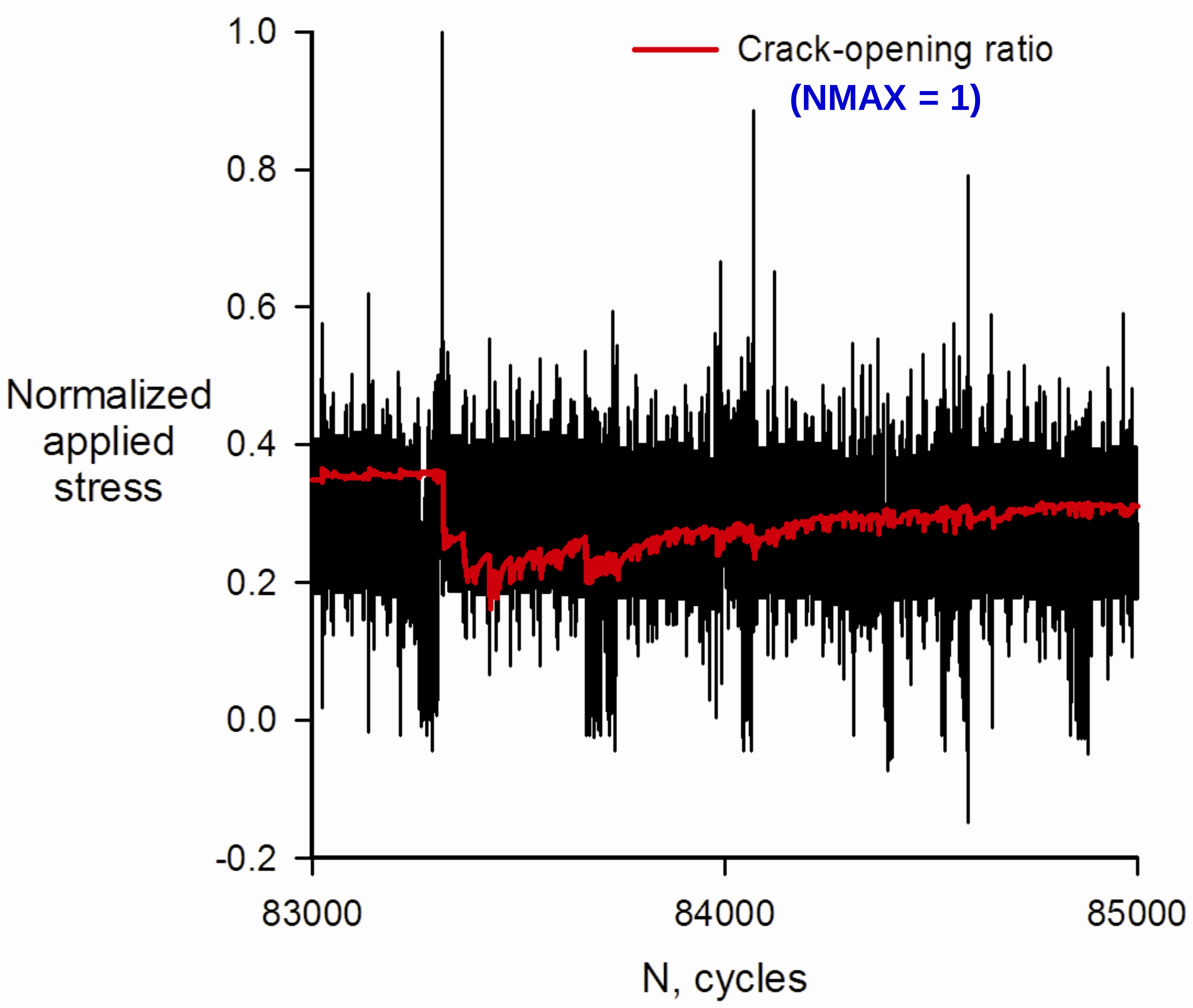
MEASURED AND PREDICTED CRACK-GROWTH UNDER TWIST SPECTRUM LOADING



Measured and Calculated Crack-Length-Against-Cycles for Modified FSFT Spectrum Loading



Typical Crack-Opening Stress Calculations for P-3C Modified FSFT Spectrum Loading



CONCLUDING REMARKS

- FASTRAN is an advanced life-prediction code, which accounts for the effects of plasticity on fatigue-crack growth behavior in metallic materials for a variety of crack configurations and loading conditions.
- “Fatigue” is crack propagation from micro-structural features for many engineering materials and fatigue lives can be predicted with small-crack theory.
- Fatigue-crack growth can be predicted reasonably well under aircraft spectrum loading with the plasticity-induced crack-closure concept.
- Constraint effects and non-linear fracture mechanics parameters are keys to improving life-prediction models.
- Fatigue-crack growth-rate data in the near threshold regime should be obtained with no load-history effects.

Future FASTRAN Modifications

- Incorporate T-stress in the evolution of plastic deformation around crack fronts (bending crack configurations have +T stresses, while tension-loaded configurations have –T stresses)

- Include roughness- and debris-induced crack-closure behavior in the model

- Development of plasticity, creep, and relaxation behavior in time-dependent crack growth during load-time-temperature cyclic histories (creep brittle and creep ductile materials)