Three Dimensional Simulation of Near-Threshold Fatigue Crack Growth for the K-Decreasing Test Method

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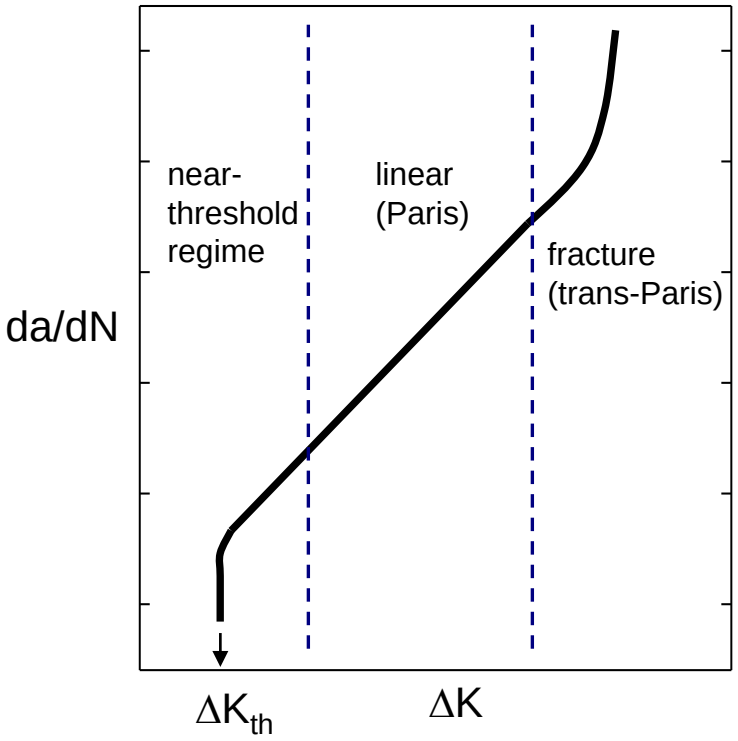
E08 Fatigue and Fracture Committee Meeting
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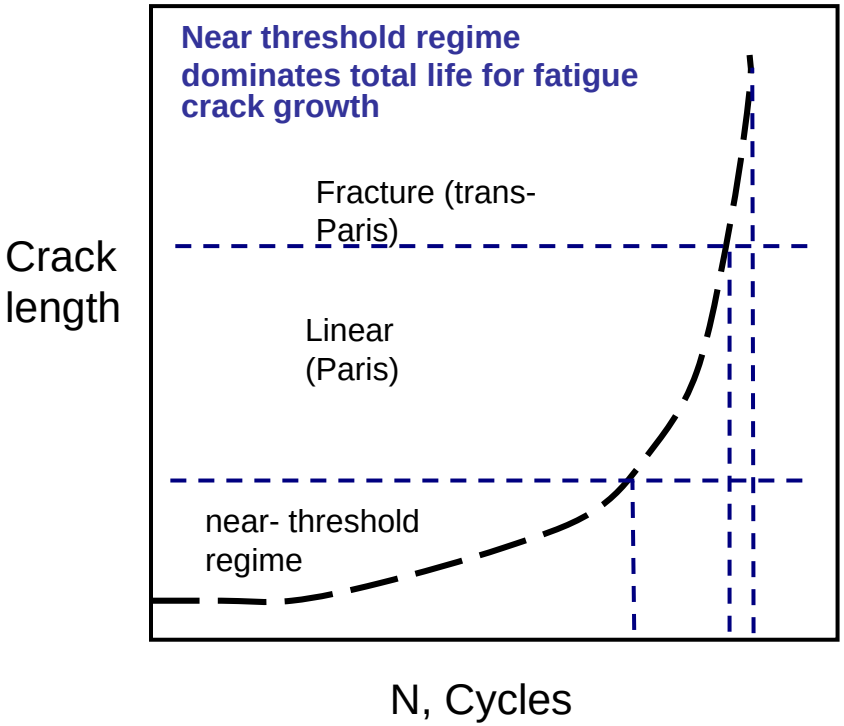
Outline

- Introduction
- Motivation
- ASTM recommended K-reduction procedures
- Objectives of the study
- 3D elastic-plastic FE simulation of different K-reduction constant-R procedure
- Results and discussion
- Concluding remarks

Introduction

- Threshold stress intensity range, ΔK_{th}, represents a level below which a crack will not grow.

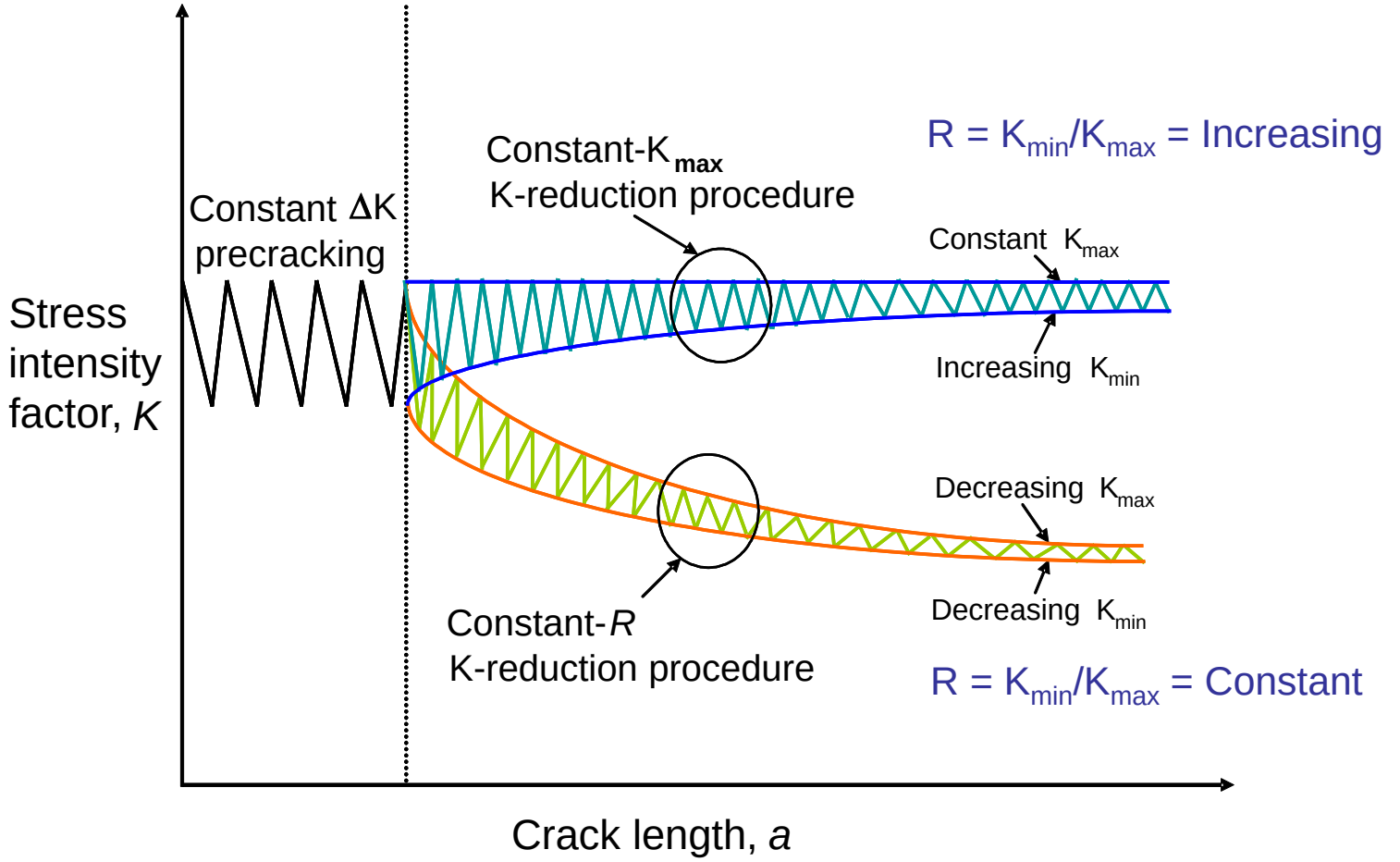




- In the threshold regime, reduced crack driving force leads to non-representative crack growth rate data

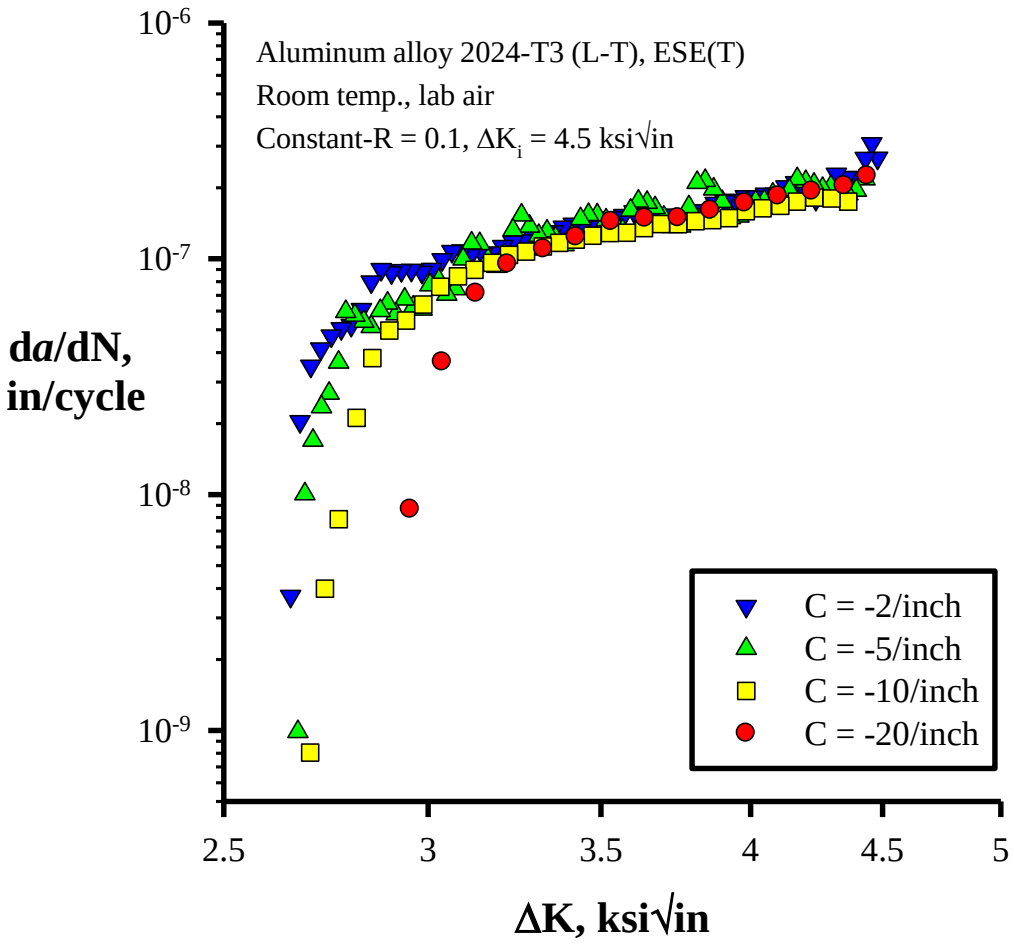
ASTM test methods (E647)

Standard test methods for measurement of fatigue crack growth rates



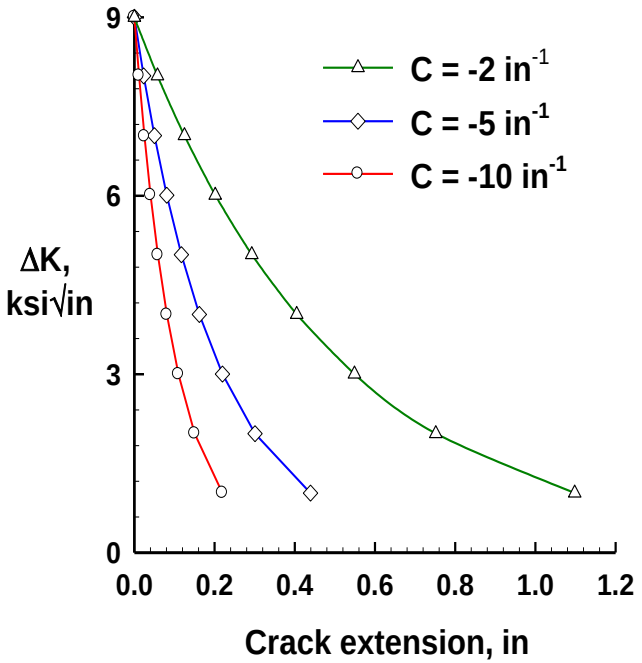
- Focus of the current presentation will be on constant-R K-reduction procedure

Motivation



ASTM E 647
$da/dN_{init} < 4x10^{-7}$ in/cycle
K-gradient (C) ≥ -2 in^{-1}

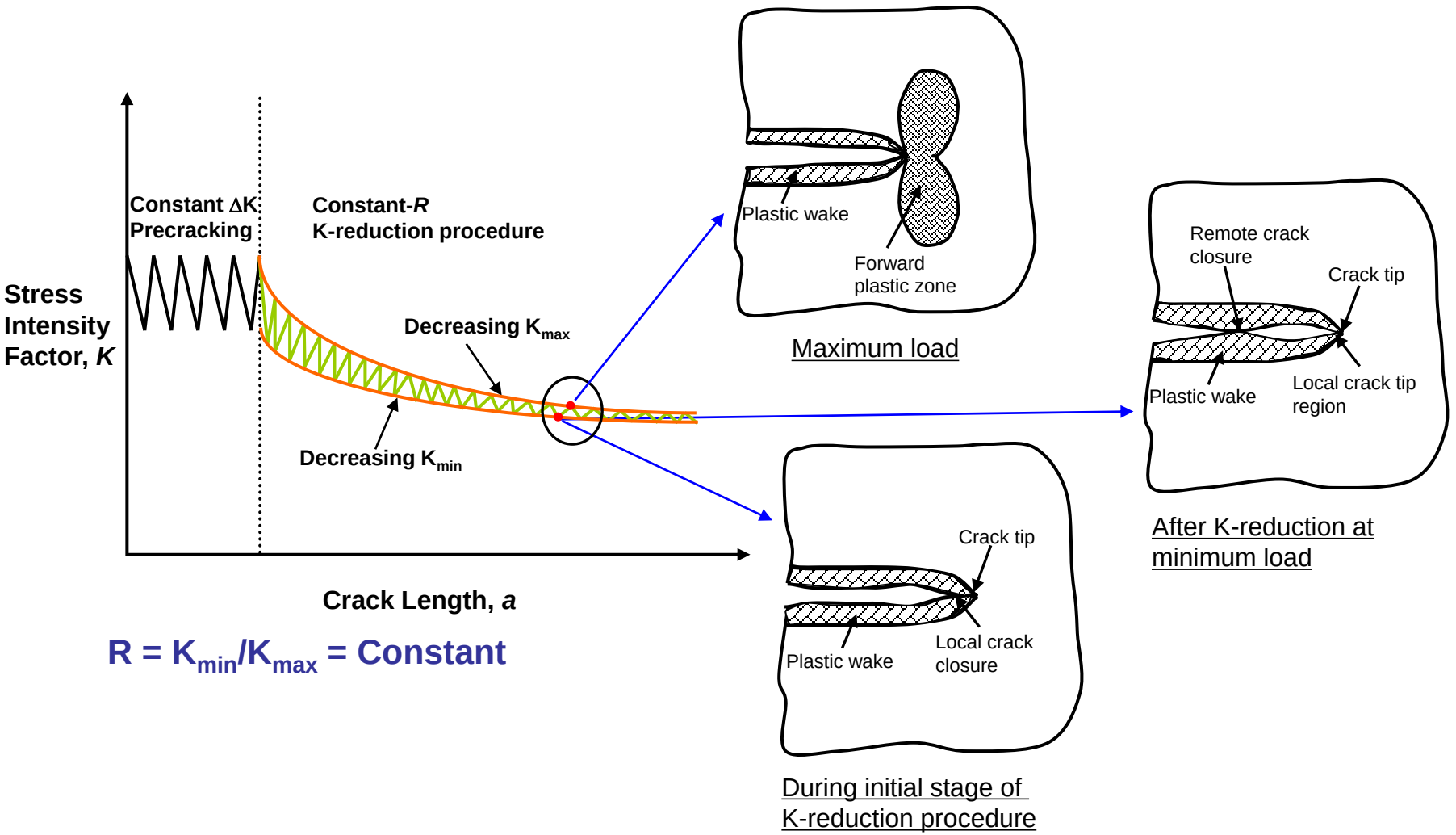
$$C = \left(\frac{1}{K}\right) \bullet \left(\frac{dK}{da}\right)$$



K-gradient steeper than ASTM E 647 (-2 in^{-1})

- Affected by K-gradient, starting K-level, residual stress, geometry, material type and environmentally assisted cracking

Remote crack closure under constant-R K-reduction procedure

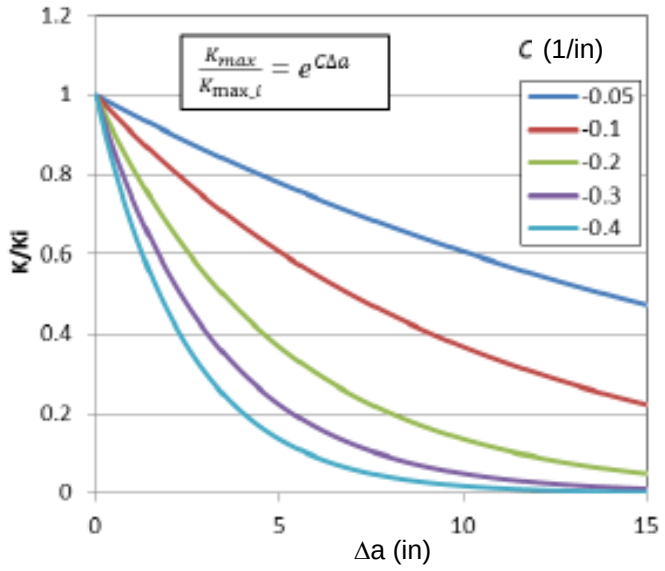


$R = K_{min}/K_{max} = \text{Constant}$

- Discontinuous crack closure leads to reduced crack tip driving force

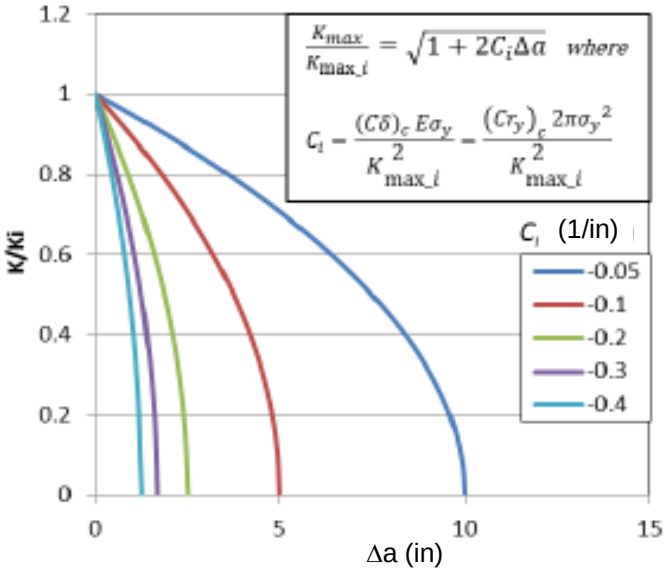
Comparison of constant C (ASTM) and constant CK^{2*} methods

Constant C (ASTM method)



$$\frac{K_{max}}{K_{max,i}} = e^{C\Delta a}$$

Constant CK^2 method

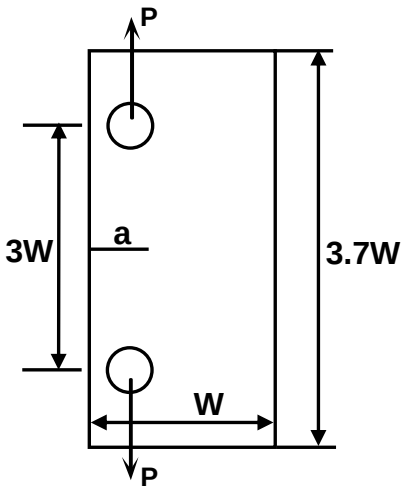


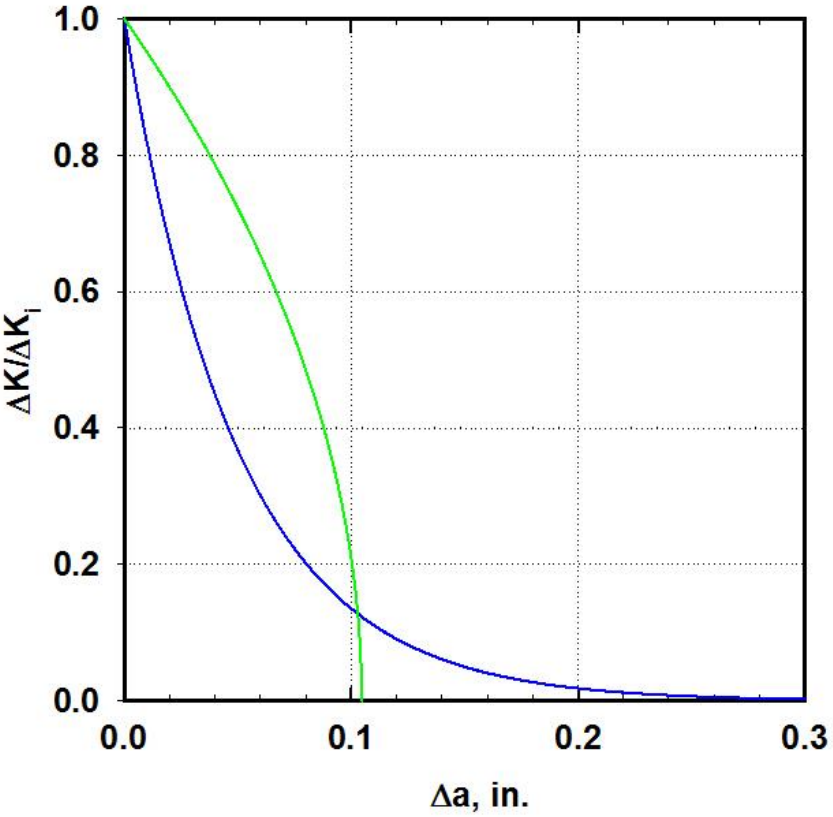
$$\frac{K_{max}}{K_{max,i}} = \sqrt{1 + 2C_i\Delta a}$$

$$C_i = \frac{(C\delta)_c E_{\sigma_y}}{K^2_{max,i}} = \frac{(Cr_y)_c 2\pi\sigma_y^2}{K^2_{max,i}}$$

* Pettit, R. G., et al., " Shed rate effects and a new axisymmetric specimen for crack growth threshold testing", 13th ASTM/ESIS Symposium on FEM (39th NFFM), Jacksonville, FL, 2013

An example of constant C (ASTM) and constant CK^2 method





Material: Ti-6-2-2-2-2

ESE(T), W = 1.5 in
B = 0.062 in

K_{max} = 20.0 ksi√in

ΔK_0 = 18.0 ksi√in

R = 0.1

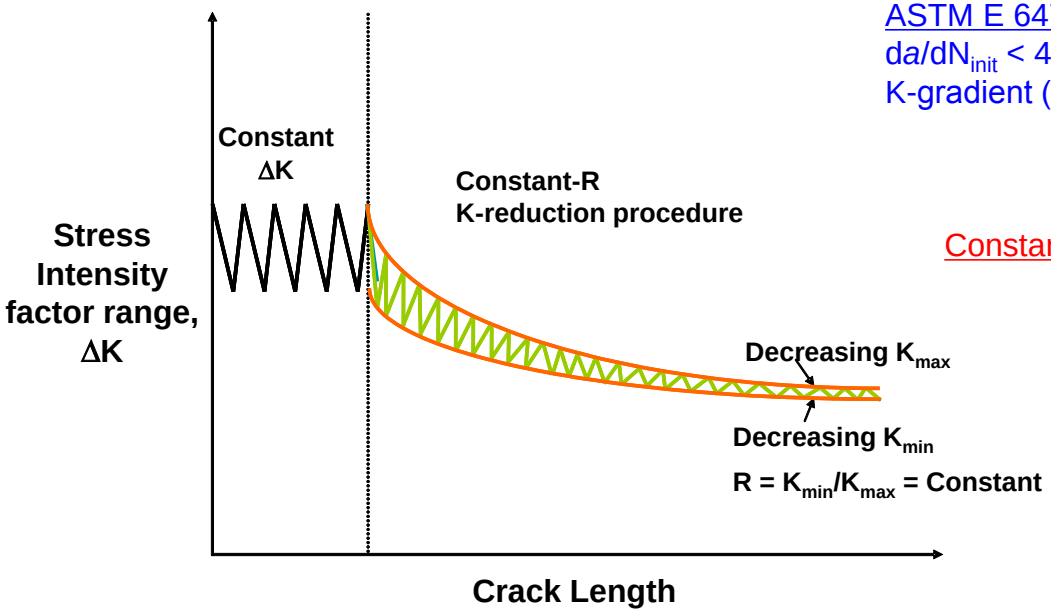
C = -20.0 in^{-1} (ASTM)

C_i = -4.78 in^{-1} (CK^2)

- Constant CK^2 method is faster when compared to constant C ASTM method

Objectives of the study

Computationally simulate constant C(ASTM) and constant CK^2 K-decreasing procedures considering plasticity induced crack closure effects.



ASTM E 647
$da/dN_{init} < 4x10^{-7}$ in/cyl
K-gradient (C) ≥ -2 in^{-1}

$$C = \left(\frac{1}{K}\right) \bullet \left(\frac{dK}{da}\right)$$

Constant CK^2

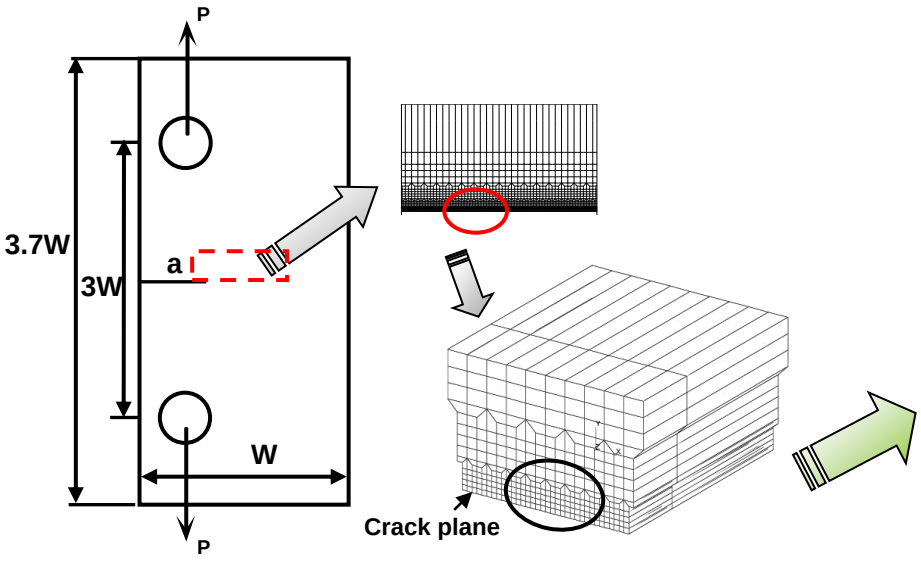
$$\frac{K_{max}}{K_{max,i}} = \sqrt{1 + 2C_i \Delta a}$$

Objective

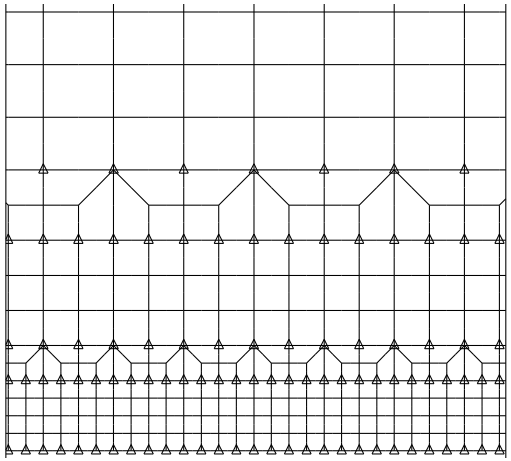
From various simulations for different material types

- a) Compare two different schemes
- b) Understand and estimate crack closure levels and their affect on crack tip driving force

3D finite element model of ESE(T) specimen



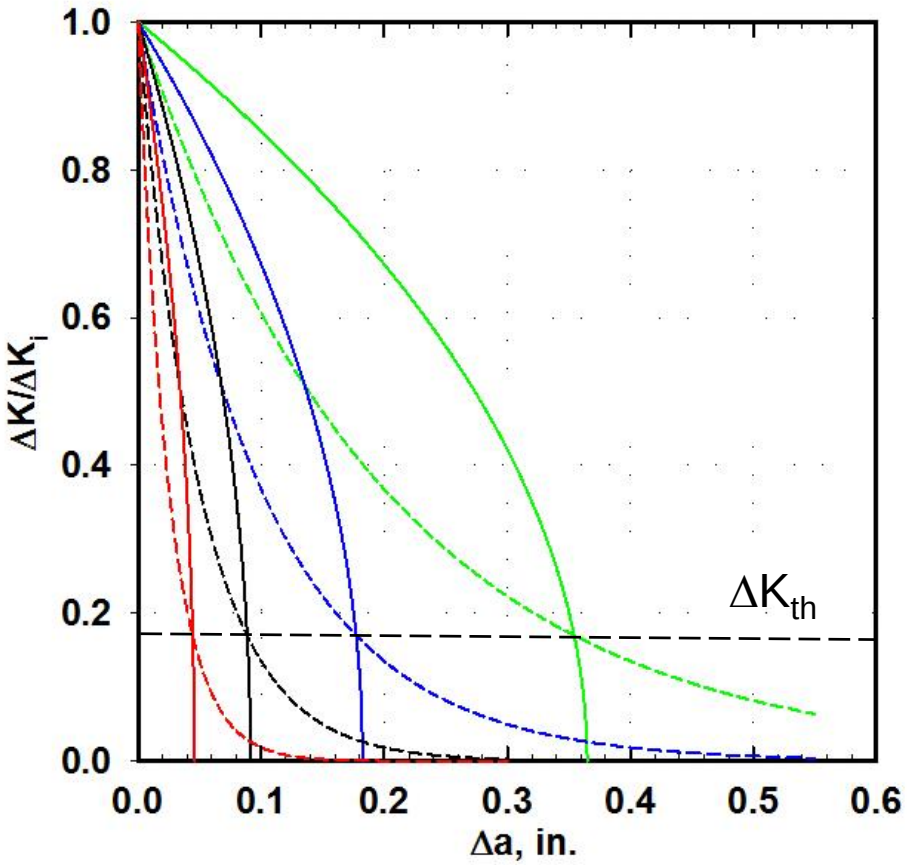
Number of nodes: 48102
Number of elements: 30,520



Capabilities of ZIP3D

- Elastic-plastic non-linear finite element code
- Element type: Brick element
- Material non-linearity: Elastic-perfectly plastic, Bilinear or Ramberg-Osgood
- Hardening : Isotropic
- Fatigue and Fracture:
  - Cyclic crack growth and crack closure simulations;
  - Evaluation of fracture parameters K and J
  - Stable crack growth using CTOA parameter

Comparison of ΔK-reduction profiles



K_{max} = 15.0 ksi√in

ΔK_0 = 13.5 ksi√in

R = 0.1

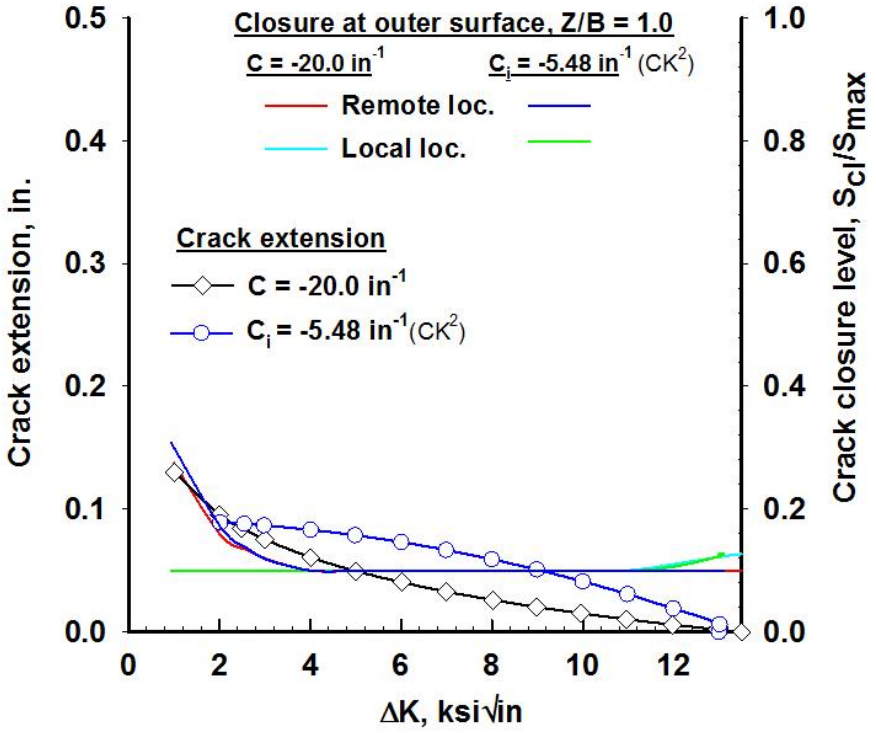
- C = -5.0 in^{-1} (ASTM)
- C_i = -1.37 in^{-1} (CK^2)
- C = -10.0 in^{-1} (ASTM)
- C_i = -2.74 in^{-1} (CK^2)
- C = -20.0 in^{-1} (ASTM)
- C_i = -5.48 in^{-1} (CK^2)
- C = -40.0 in^{-1} (ASTM)
- C_i = -10.96 in^{-1} (CK^2)

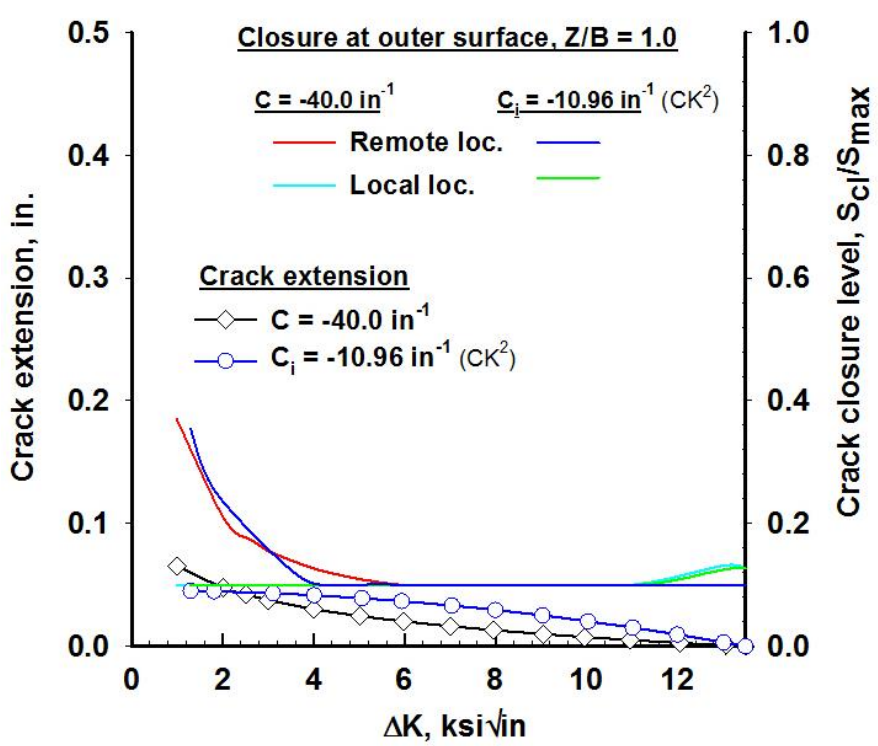
- Constant CK^2 profile can be developed for same total crack growth
  - CK^2 method will approach ΔK_{th} in less overall time
  - CK^2 method starts at a slower gradient moving away from the largest plastic zone

Variation in crack closure levels

Material: Ti-6-2-2-2, ESE(T), W = 1.5 in, B = 0.062 in

K_{max} = 15.0 ksi√in, ΔK_o = 13.5 ksi√in, R = 0.1



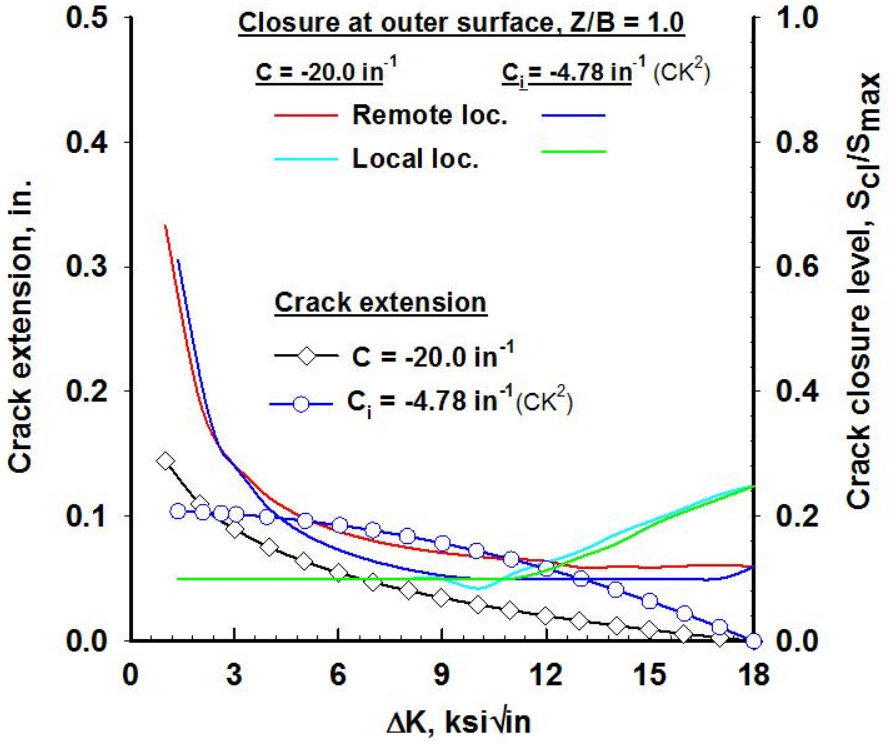


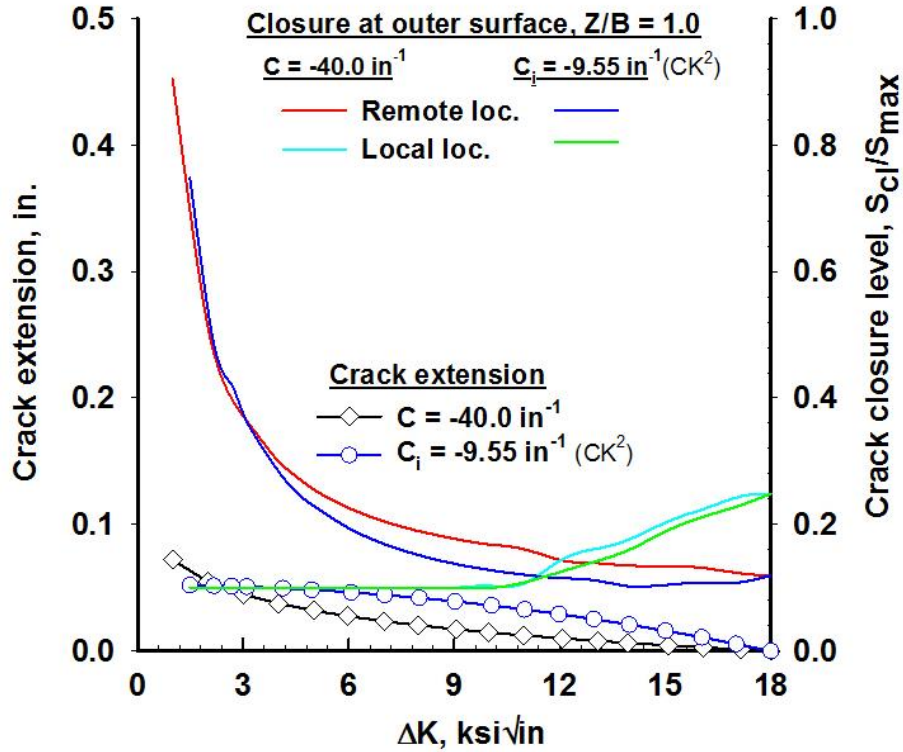
- Faster K-decreasing rate leads to greater remote crack closure

Variation in crack closure levels …

Material: Ti-6-2-2-2, ESE(T), W = 1.5 in, B = 0.062 in

K_{max} = 20.0 ksi√in, ΔK_o = 18.0 ksi√in, R = 0.1



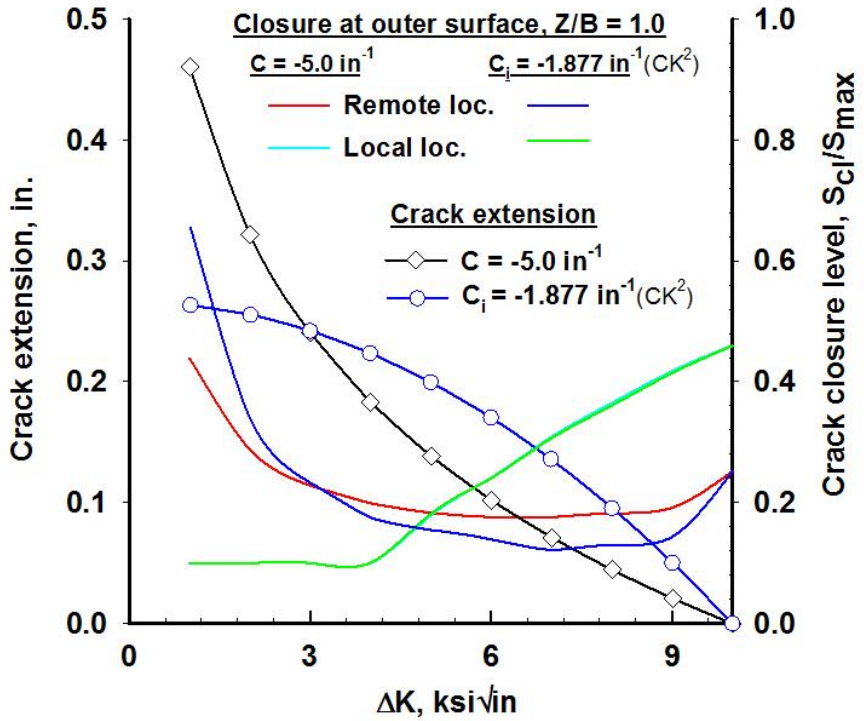


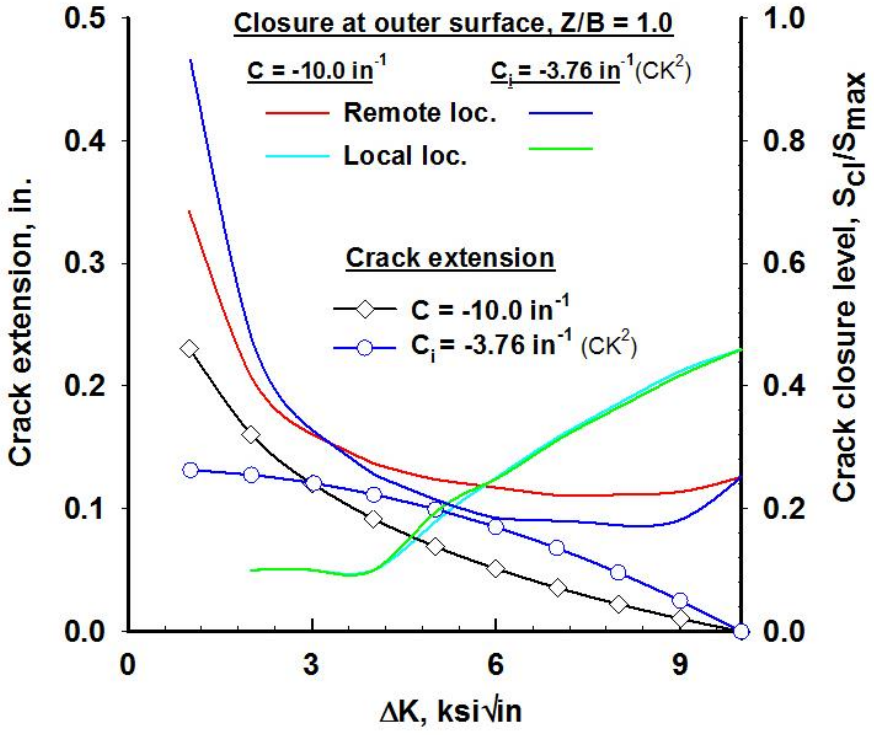
- Increase in $K_{max,i}$ leads to higher remote crack closure for both the test methods

Variation in crack closure levels

Material: Al-2024-T3, ESE(T), W = 1.5 in, B = 0.09 in

K_{max} = 11.11 ksi√in, ΔK_o = 10.0 ksi√in, R = 0.1



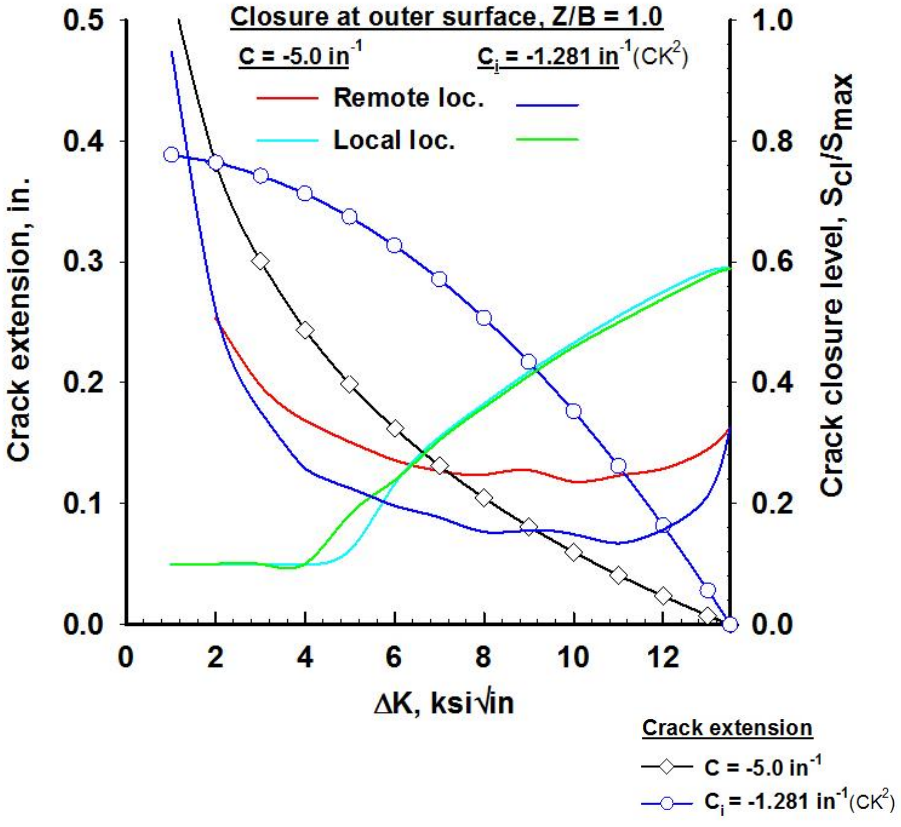


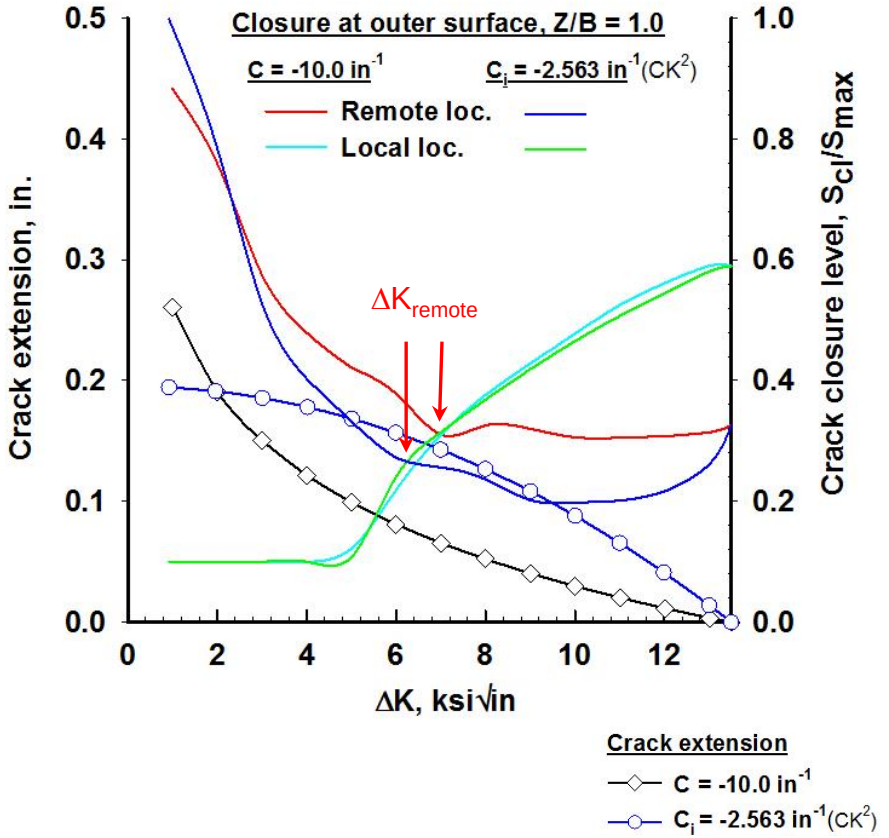
- Faster K-decreasing rate leads to greater remote crack closure

Variation in crack closure levels …

Material: Al-2024-T3, ESE(T), W = 1.5 in, B = 0.09 in

K_{max} = 15.0 ksi√in, ΔK_o = 13.5 ksi√in, R = 0.1





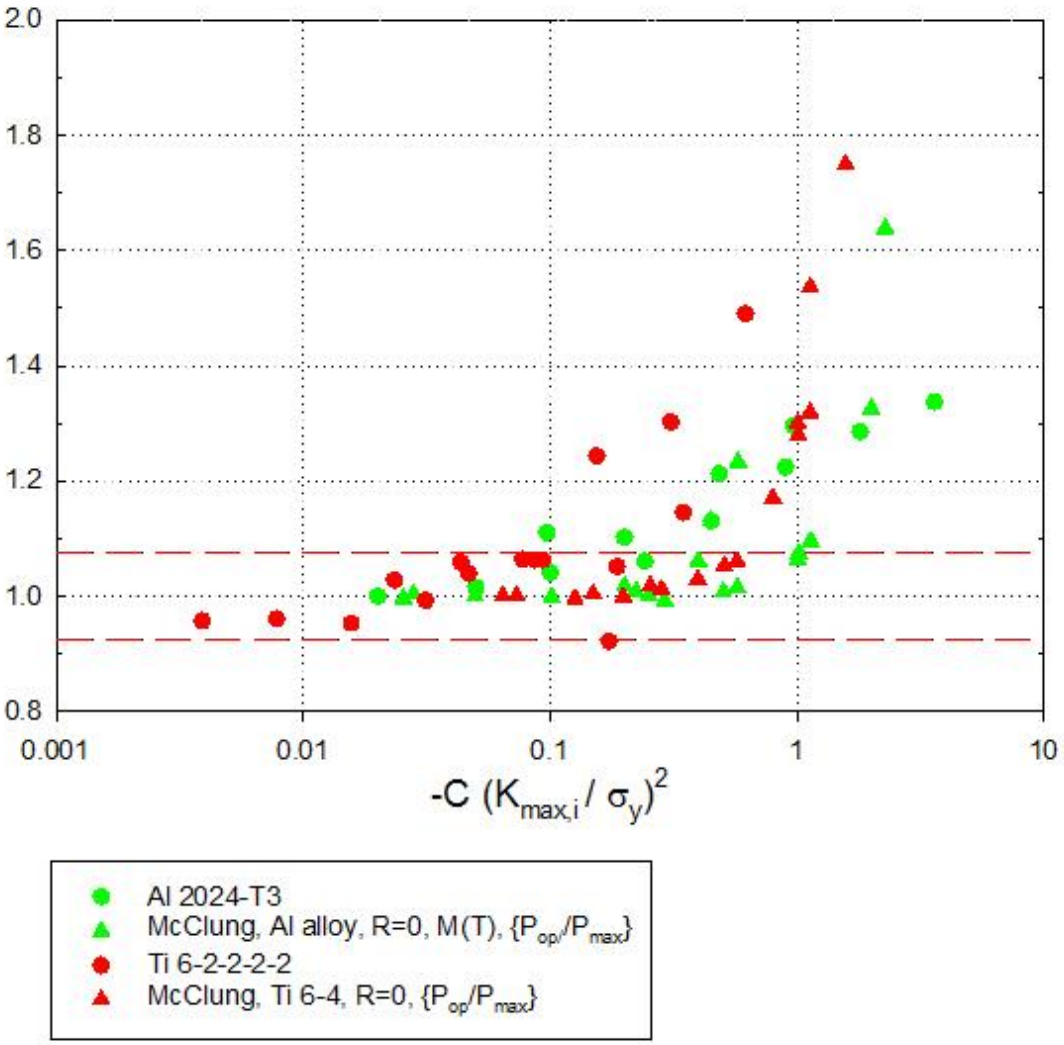
- Increase in $K_{max,i}$ leads to higher remote crack closure for both the test methods

Comparison of normalized data for ASTM constant 'C' method

$$\frac{\Delta K_{remote}}{\Delta K_{th,baseline}}$$

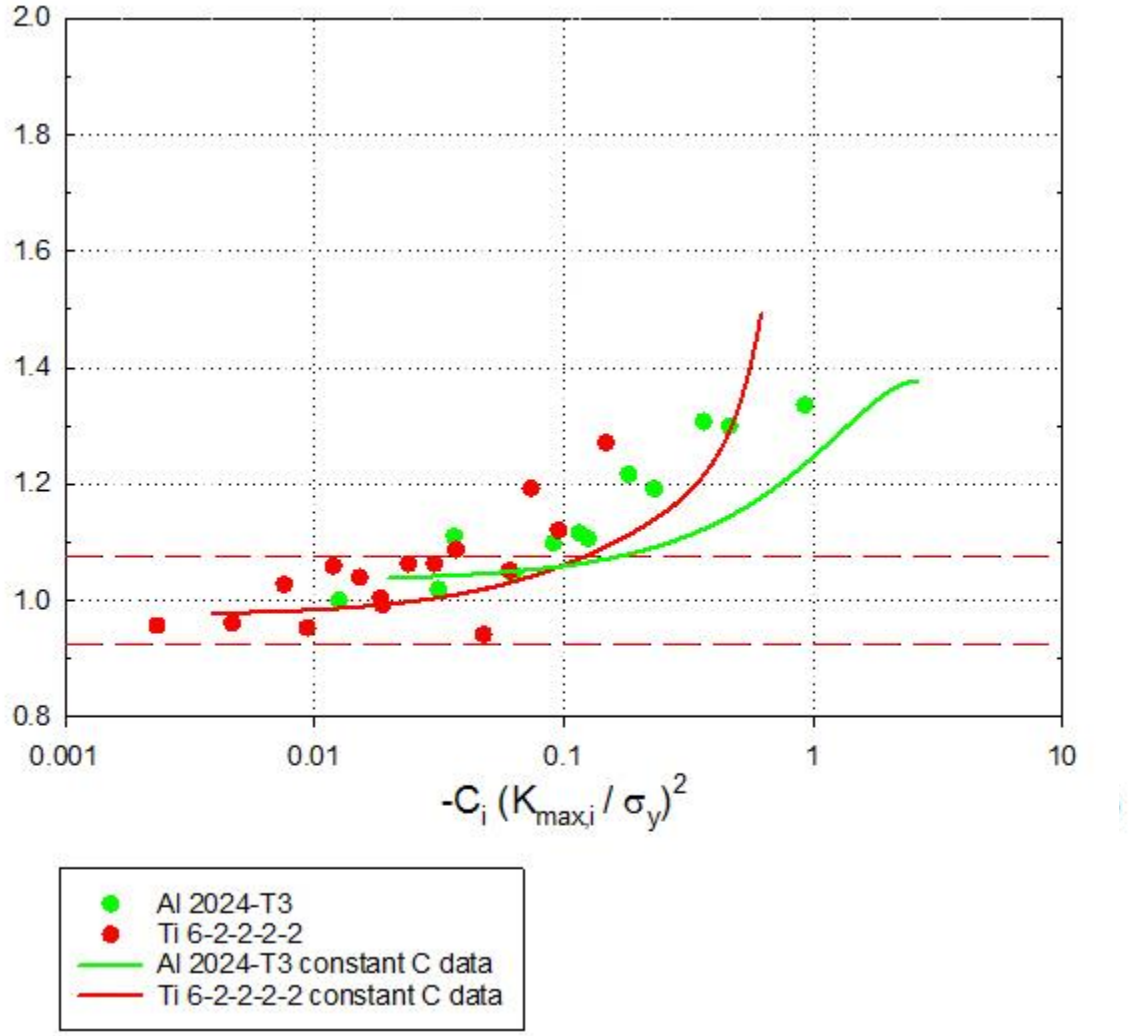
or

$$\frac{P_{op}/P_{max}}{P_{op}/P_{max}(baseline)}$$

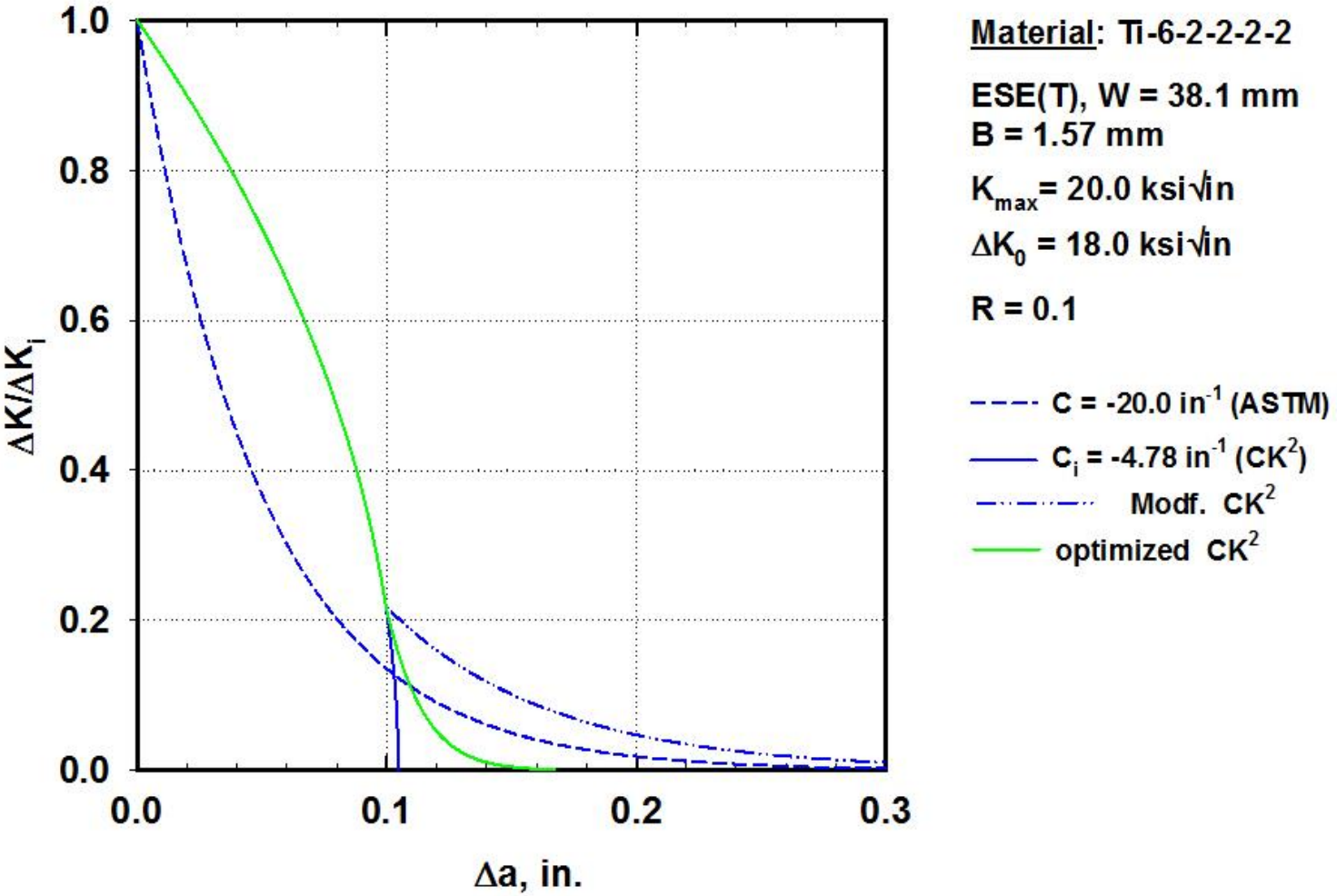


Comparison of normalized data for constant 'CK^2' method

$$\frac{\Delta K_{remote}}{\Delta K_{th,baseline}}$$



Optimization of ΔK-reduction profile



- Possible to design an optimized K-decreasing sequence to minimize the affects of remote crack closure on crack tip driving force

Concluding Remarks

- ✓ 3-D FE models developed to simulate different ΔK-reduction procedures for two different materials
  - ✓ Remote and local crack closure measurements made using simulation results
  - ✓ Remote closure was shown to occur for certain testing parameters for both the procedures
- ✓ CK^2 method results in less remote closure than the constant C method for equivalent procedures
- ✓ K-decreasing procedure can be optimized to minimize the affect of remote crack closure. Needs to be further explored

Numerical simulations aid in understanding and optimizing different K-decreasing procedures