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

Banavara R. Seshadri
National Institute of Aerospace

Stephen W. Smith
NASA Langley Research Center

John A. Newman
NASA Langley Research Center

Richard G. Pettit
FractureLab

E08 Fatigue and Fracture Committee Meeting
May 19 2015, Anaheim, CA
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
• Threshold stress intensity range, $\Delta K_{th}$, 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.
Standard test methods for measurement of fatigue crack growth rates

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

Aluminum alloy 2024-T3 (L-T), ESE(T)
Room temp., lab air
Constant-R = 0.1, \( \Delta K_i = 4.5 \text{ ksi} \sqrt{\text{in}} \)

\[ \frac{da}{dN}, \text{ in/cycle} \]

\[ d \Delta K_i, \text{ ksi} \sqrt{\text{in}} \]

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

ASTM E 647
\( \frac{da}{dN_{init}} < 4 \times 10^{-7} \text{ in/cycle} \)
K-gradient (C) \( \geq -2 \text{ in}^{-1} \)

\[ C = \left( \frac{1}{K} \right) \left( \frac{dK}{da} \right) \]

K-gradient steeper than ASTM E 647 (-2 in\(^{-1}\))
Remote crack closure under constant-R K-reduction procedure

Discontinuous crack closure leads to reduced crack tip driving force.

\[ R = \frac{K_{\text{min}}}{K_{\text{max}}} = \text{Constant} \]
Comparison of constant C (ASTM) and constant $C K^2$ methods

**Constant C (ASTM method)**

\[ \frac{K_{\text{max}}}{K_{\text{max},i}} = e^{C \Delta a} \]

**Constant $C K^2$ method**

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

where

\[ C_i = \frac{(C\delta)_c E \sigma_y}{K_{\text{max},i}^2} = \frac{(Cr_y)_c 2\pi \sigma_y^2}{K_{\text{max},i}^2} \]

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

- Constant $C K^2$ 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.

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

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

Number of nodes: 48102
Number of elements: 30,520
Comparison of $\Delta K$-reduction profiles

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

$K_{max} = 15.0$ ksi $\sqrt{\text{in}}$
$\Delta K_0 = 13.5$ ksi $\sqrt{\text{in}}$
$R = 0.1$

- $C = -5.0$ 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$^{-1}$ ($CK^2$)
Variation in crack closure levels

Material: Ti-6-2-2-2, ESE(T), W = 1.5 in, B = 0.062 in
\[ K_{\text{max}} = 15.0 \text{ ksi/in}, \Delta K_o = 13.5 \text{ ksi/in}, R = 0.1 \]

- Faster K-decreasing rate leads to greater remote crack closure
Material: Ti-6-2-2-2, ESE(T), W = 1.5 in, B = 0.062 in

\[ K_{\text{max}} = 20.0 \text{ ksi}\sqrt{\text{in}}, \Delta K_o = 18.0 \text{ ksi}\sqrt{\text{in}}, R = 0.1 \]

- Increase in \( K_{\text{max},i} \) leads to higher remote crack closure for both the test methods
Material: Al-2024-T3, ESE(T), W = 1.5 in, B = 0.09 in

\[ K_{\text{max}} = 11.11 \text{ ksi} \sqrt{\text{in}}, \Delta K_0 = 10.0 \text{ ksi} \sqrt{\text{in}}, R = 0.1 \]

Variation in crack closure levels

- 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

\[ K_{\text{max}} = 15.0 \text{ ksi} \sqrt{\text{in}}, \Delta K_o = 13.5 \text{ ksi} \sqrt{\text{in}}, R = 0.1 \]

- Increase in \( K_{\text{max},i} \) leads to higher remote crack closure for both the test methods.
Comparison of normalized data for ASTM constant ‘C’ method

\[
\frac{\Delta K_{\text{remote}}}{\Delta K_{\text{th,baseline}}} \\
\text{or} \\
\frac{P_{\text{op}}}{P_{\text{max}}} \\
\frac{P_{\text{op}}}{P_{\text{max}}(\text{baseline})}
\]

\[ -C \left( \frac{K_{\text{max},i}}{\sigma_y} \right)^2 \]
Comparison of normalized data for constant ‘CK^2’ method

\[ \frac{\Delta K_{\text{remote}}}{\Delta K_{\text{th, baseline}}} \]
Optimization of $\Delta K$-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 $\Delta K$-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