Precision Threshold Testing Using the Flat Bottom Hole (FBH) Specimen

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Overview

- Threshold testing background
- Description of FBH specimen
- Shed rate effects revisited
  - Application to conventional specimens
  - Application to the FBH specimen
- Summary

Threshold Testing Background

- ΔK_{th} → The asymptotic boundary between growth and no growth of a steady-state crack
- Historically involves pre-cracking at a higher load, and load shedding until the crack “stops”
  - Shed rate, starting K, yield strength, and choice of specimen can conspire to give artificially high results not well controlled by ASTM guidelines
- Search for improved test method continues

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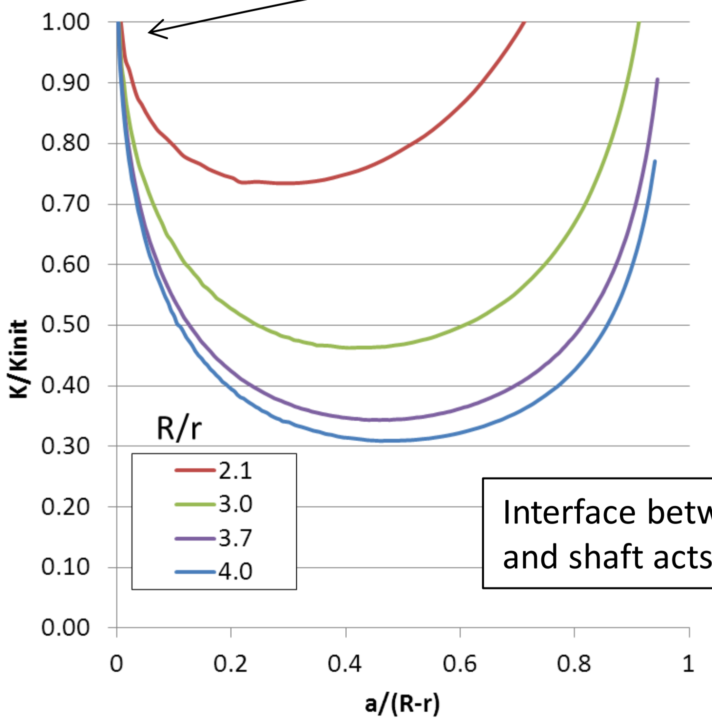
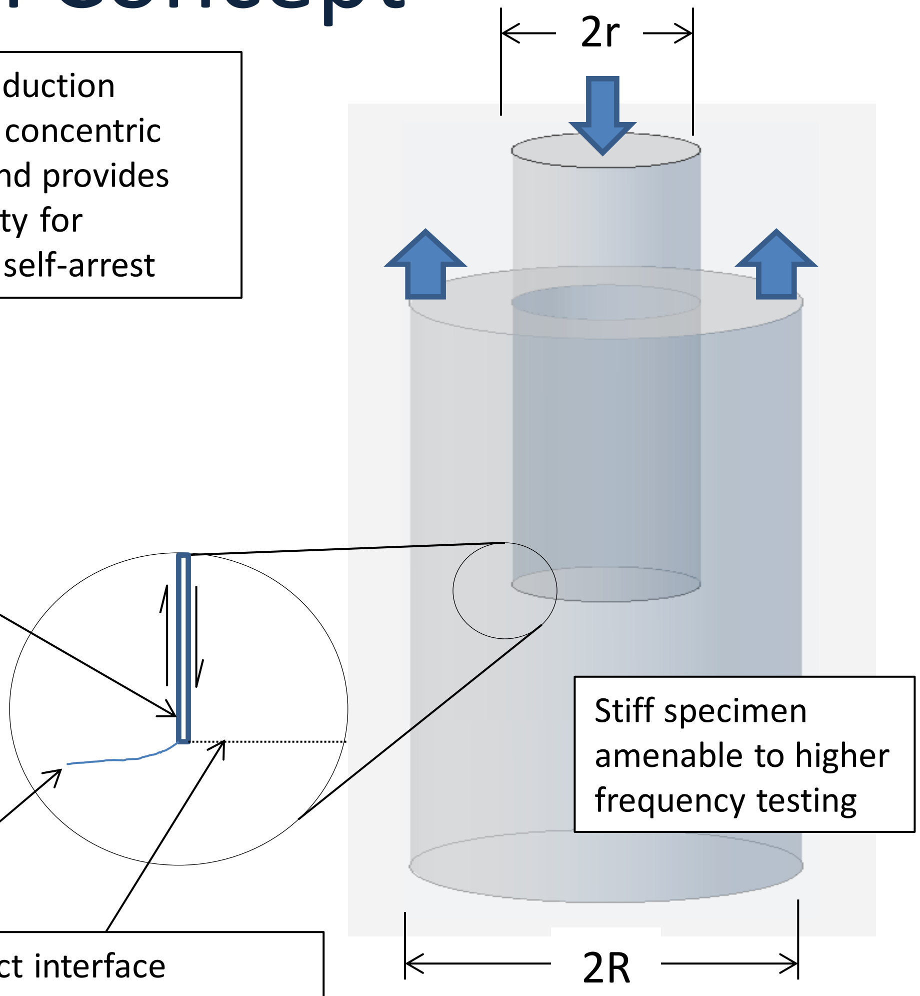
Flat Bottomed Hole (FBH) Specimen Concept



Initial K reduction promotes concentric growth, and provides opportunity for specimen self-arrest



Interface between hole and shaft acts like crack

Crack propagation with circular crack front--*no intersection with free surface*

Contact interface (acts like monolithic part)

Stiff specimen amenable to higher frequency testing

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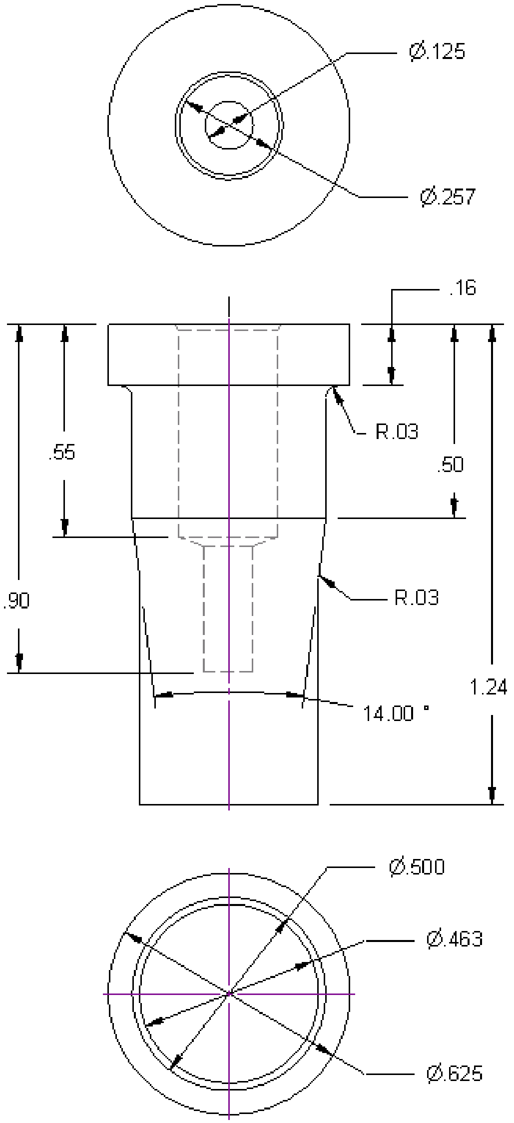
FBH Specimen, R/r=3.7

- Small sample size (0.63 DIA x 1.75 blank)
- .34x drop in K
- Can produce 2-3 thresholds/test
- Includes furnace retention shoulder
- K-solution within 0.5%



Test Rig

- Piezoelectric drive
- High frequency, low load amplitude
  - Test frequencies approaching 300 Hz demonstrated (for highest R-ratios)
  - 3 Kips max load (~1300 P-P variable)
- Integrated heating chamber
  - Up to 1400F
  - Shorter assembly for Room Temp
- Patent pending

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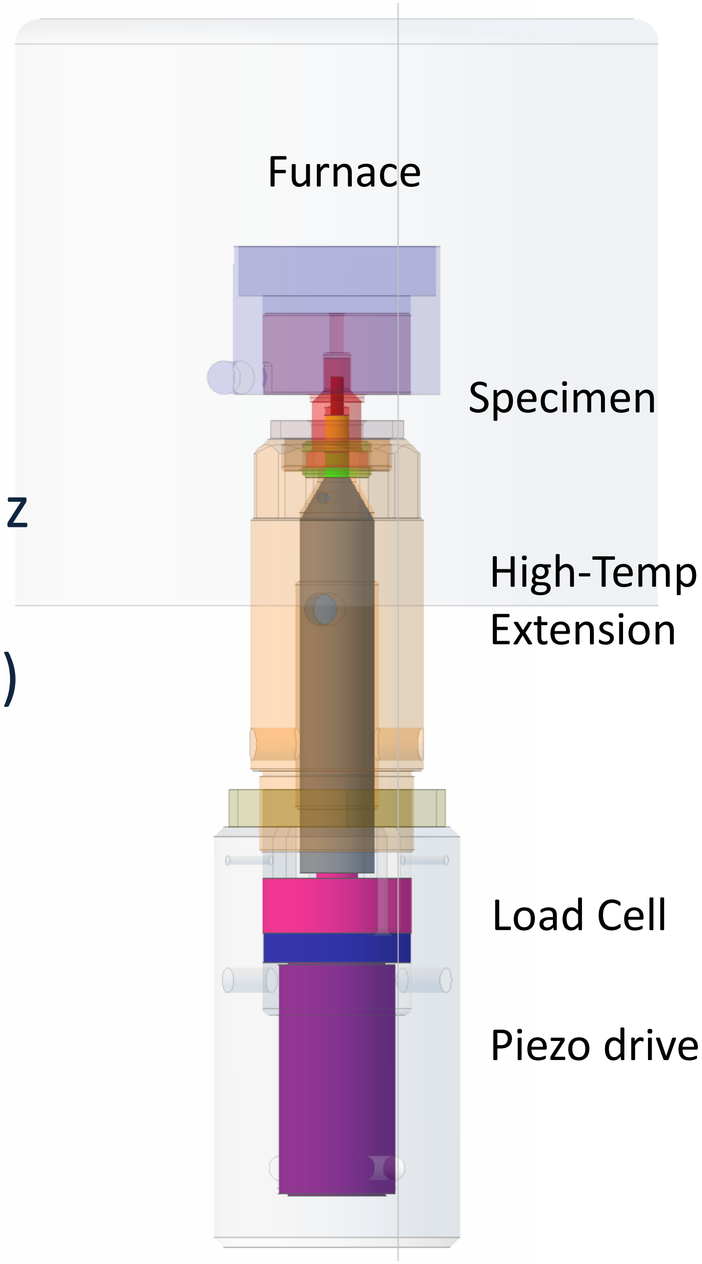
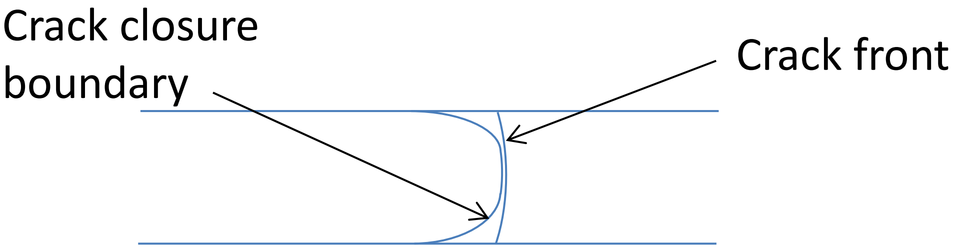


Free Surface Effect on Closure

- Schijve* and others have observed that crack closure is concentrated near where the crack front intersects a free surface.



- A specimen configuration without a free surface intersection would have a uniform closure state, eliminating a potential source of specimen dependence, and better simulate cracks in thick structures

*ASTM STP 982, pp. 5-34, 1988

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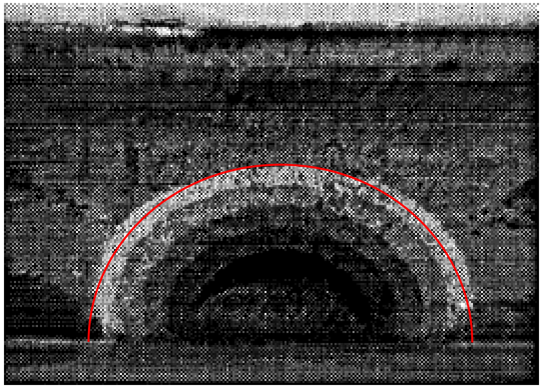
Shape Effects on Crack Propagation Data

- Actual crack shape often differs significantly from assumed shape



Forman, Mettu, NASA TM 102165

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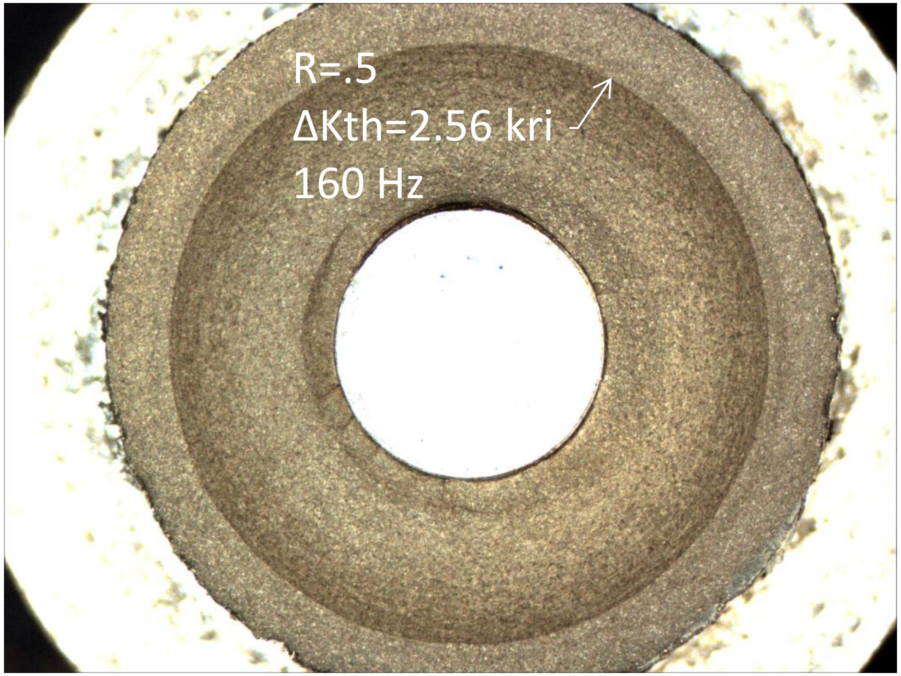
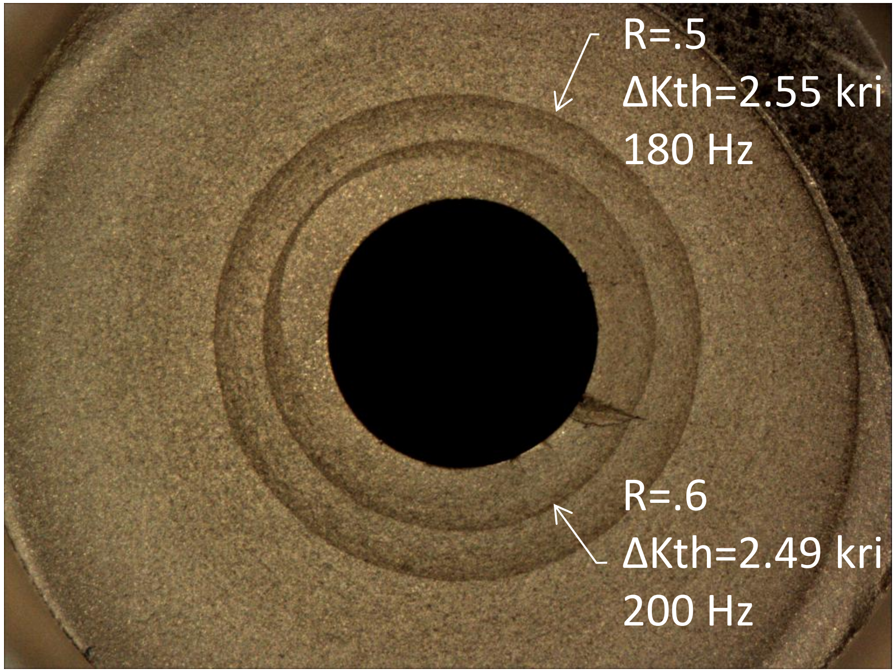
Some FBH Test Results

4142 Steel, 132 ksi yield, RT



Specimen #28, 1300 lb. max



Specimen #29, 1200 lb. max

- ΔK_{th} determined from final crack size
- Highly concentric , circular propagation yields precision results

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Advantages of FBH Specimen

- No preflaw required
- Small specimen size (.63 DIA x 1.75 blank)
- Uniform crack closure state across crack front (no free surface intersection)
- Crack front shape precisely known (circular & self-centering)
- Stiff specimen loading set-up; enables high testing at high frequency
- **Favorable natural K-shed behavior allow threshold testing at constant load, and mitigates test artifact associated with conventional specimens**

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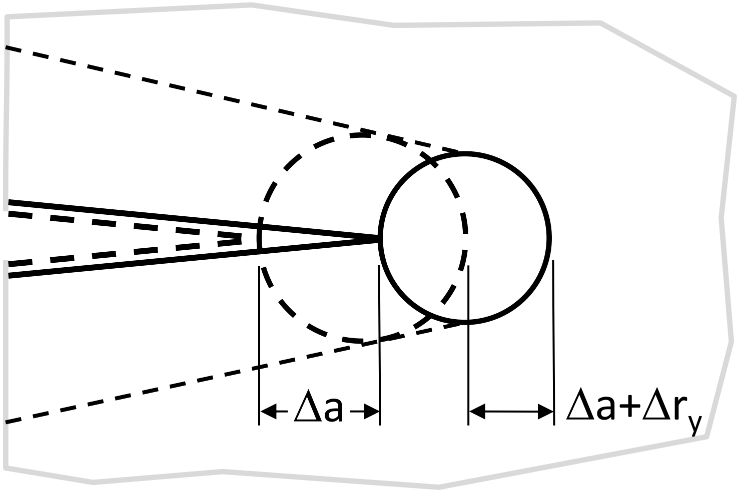
In Search of a Physically Meaningful Shed Parameter

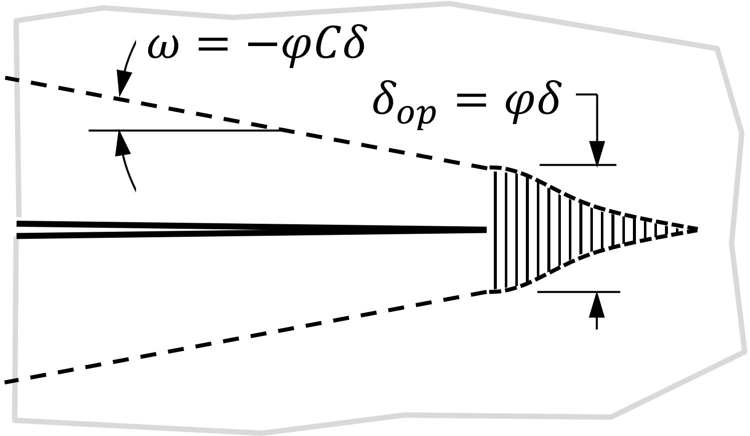
$C = \frac{dK/da}{K}$ is dimensional and a poor predictor of artifact due to retardation



$$\frac{dr_y}{da} = \frac{d(a+r_y)}{da} - 1 = 2Cr_y = -Const$$

$$r_y = \frac{1}{2\pi}\left(\frac{K_{max}}{\sigma_y}\right)^2$$

A **constant Cr$_y$** shed rate follows Wheeler's premise that retardation is caused by the plastic zone.



$$\frac{d\delta}{da} = 2C\delta = -Const$$

$$\delta = \frac{K_{max}{}^2}{E\sigma_y}$$

A **constant Cδ** shed rate is consistent with a closure mechanism. The work of Budiansky and Hutchinson suggests that for a constant R-ratio test, φ is constant.

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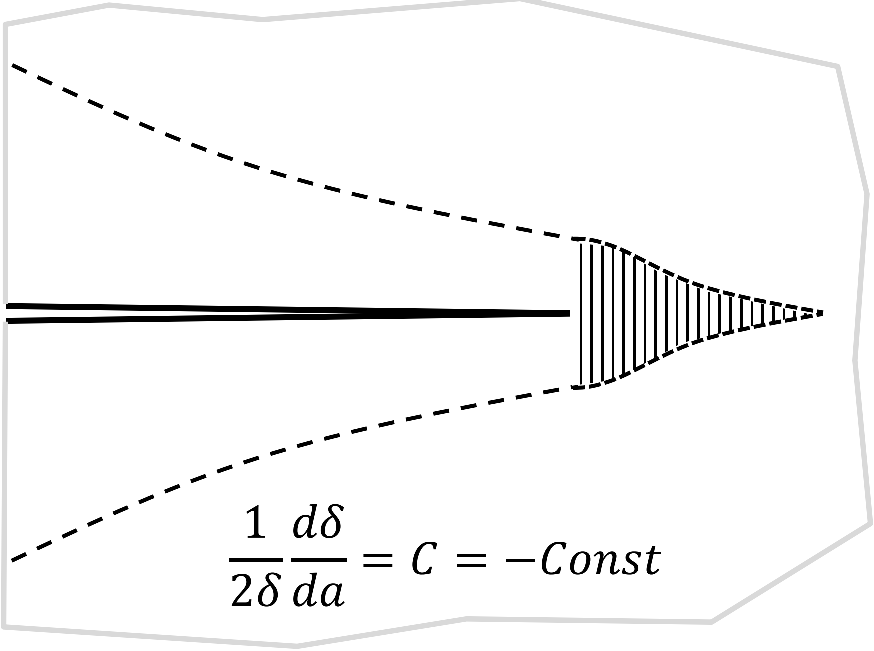
Best Correlation

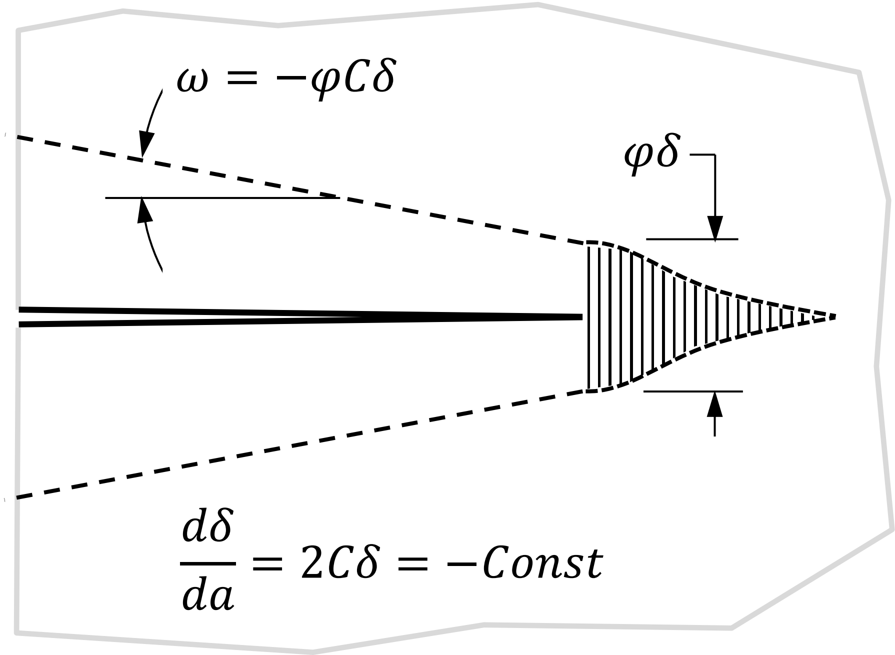
Wake Shapes Due to K-Shed Methods



$$\frac{1}{2\delta}\frac{d\delta}{da} = C = -Const$$

$$\delta = \delta_o e^{2C(a-a_o)}$$

ASTM K-shed at Constant C



$$\frac{d\delta}{da} = 2C\delta = -Const$$

$$\delta = \delta_o + 2C\delta(a - a_o)$$

K-shed at Constant Cδ

- K-shed at constant Cδ results in constant plastic wake angle, thus similarity between different stages of crack growth

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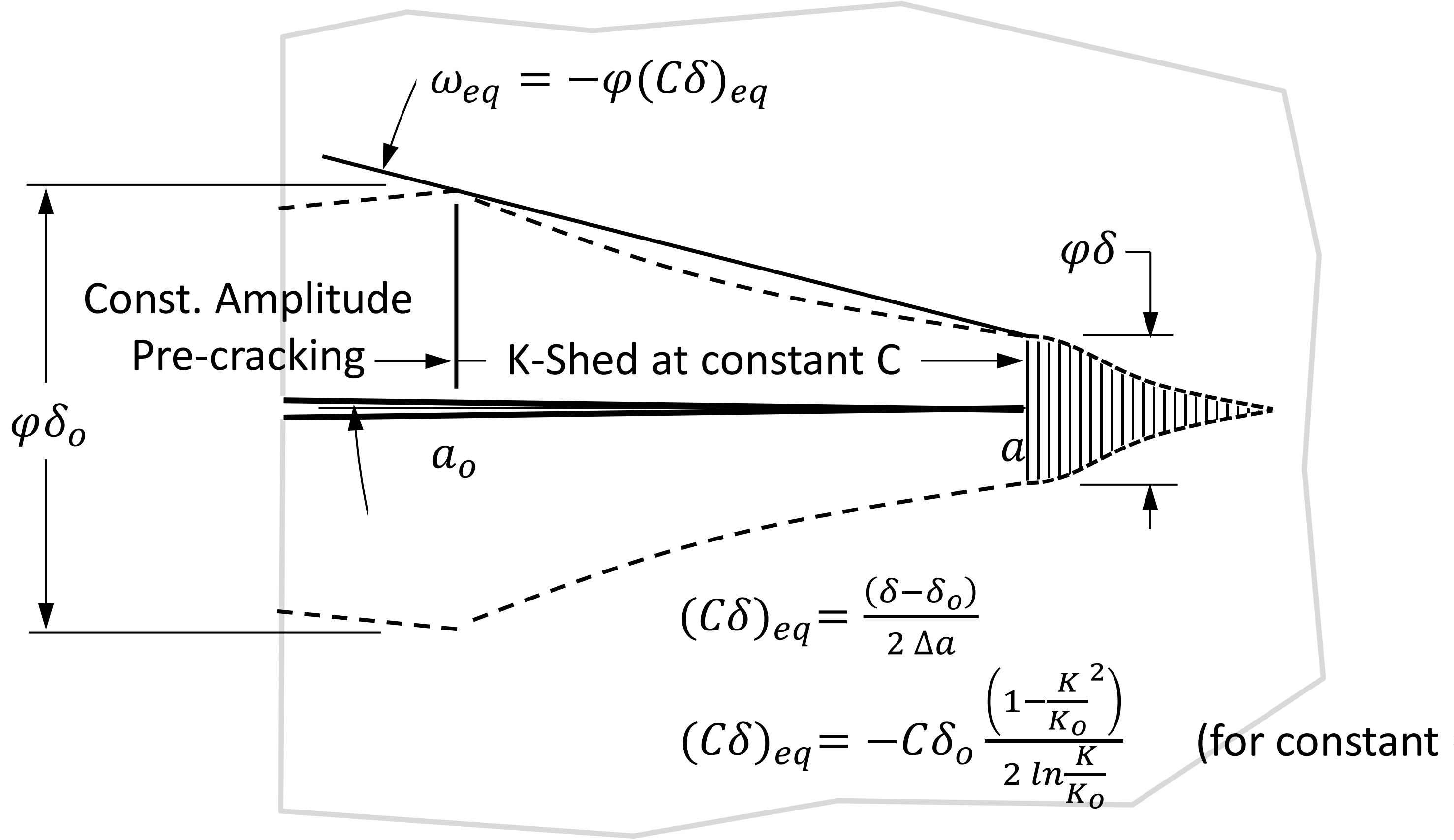
Equivalent Dimensionless Shed Rate

Idealized view for constant C test with crack nearly closed



$$(C\delta)_{eq} = \frac{(\delta-\delta_o)}{2\,\Delta a}$$

$$(C\delta)_{eq} = -C\delta_o \frac{\left(1-\frac{K}{K_o}^{2}\right)}{2\,ln\frac{K}{K_o}}$$

(for constant

- $(C\delta)_{eq}$ is based on the minimum envelope that the actual wake fits within, including effects of both C and initial K_{max}

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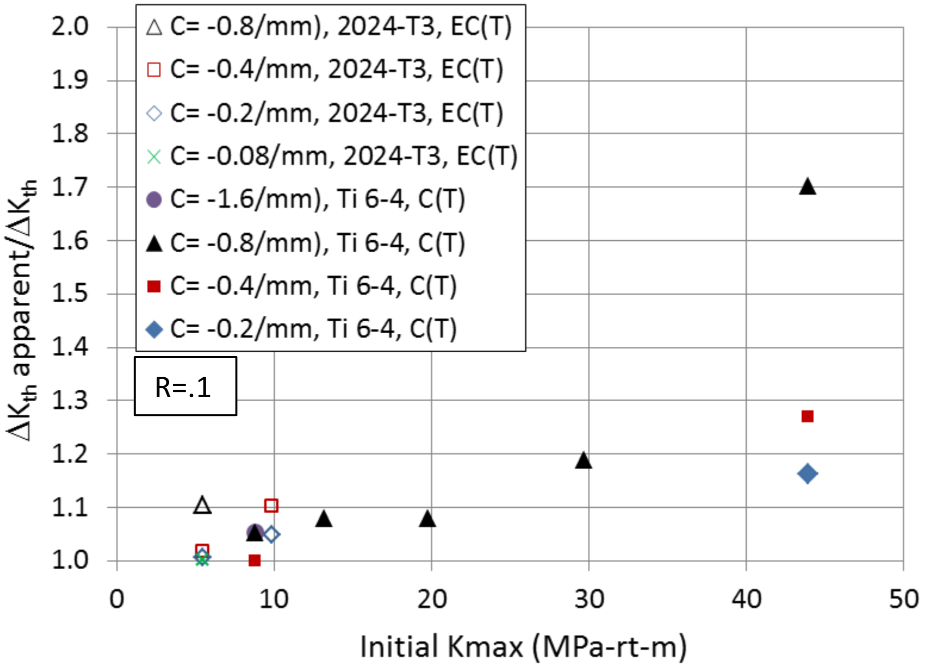
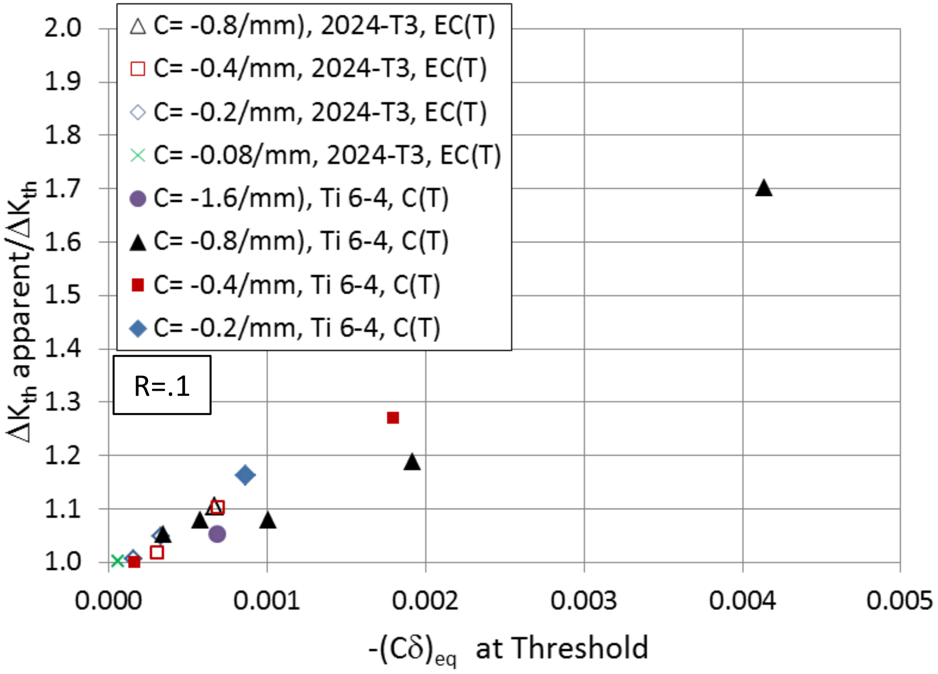
Correlation of Threshold Test Data

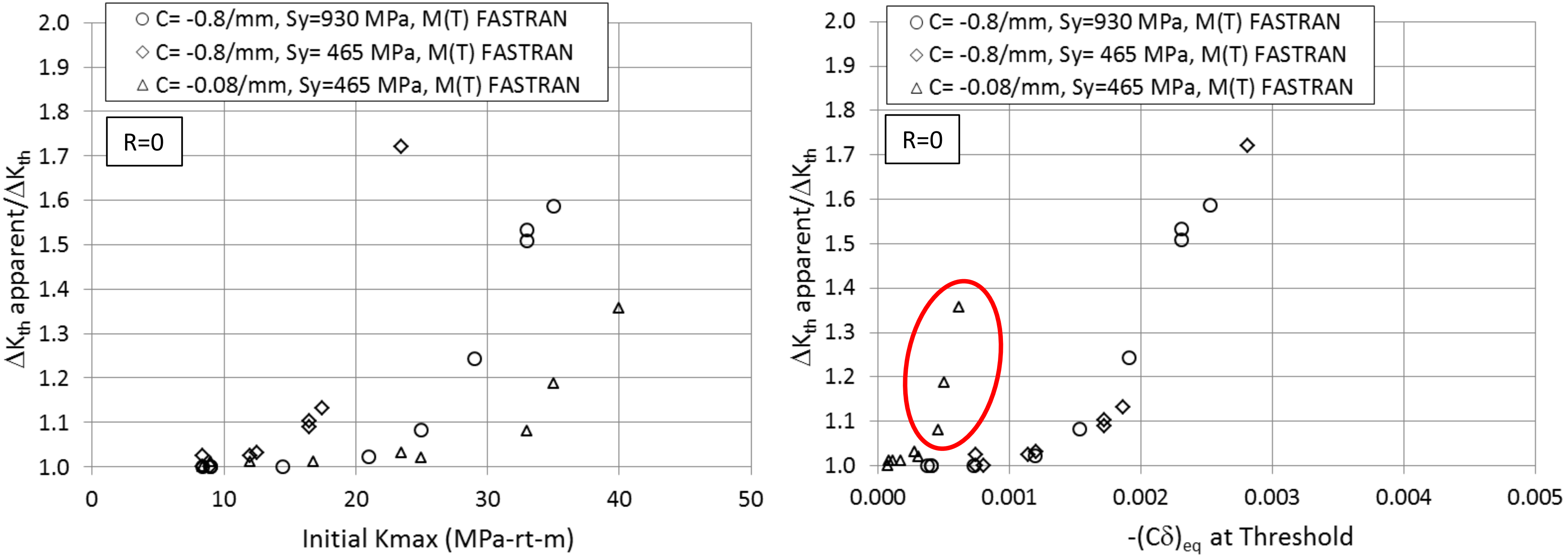




- $(C\delta)_{eq}$ alone yields fair correlation of Al and Ti data with two different specimen types and various test parameters.

2024-T3 data , JA Newman , NASA LaRC
Ti 6-4 forging data, Sheldon, Bain, Donald (1999)
Actual ΔKth taken as lowest value obtained in each.

Correlation of FASTRAN Predictions



- $(C\delta)_{eq}$ collapses yield strength effect quite well, but slowest shed rate poorly correlated at high initial K_{max}

FASTRAN results based on McClung (2000).
Threshold ratio based on ΔKeff /min ΔKeff
at applied ΔK of 5.5 Mpa for each group.

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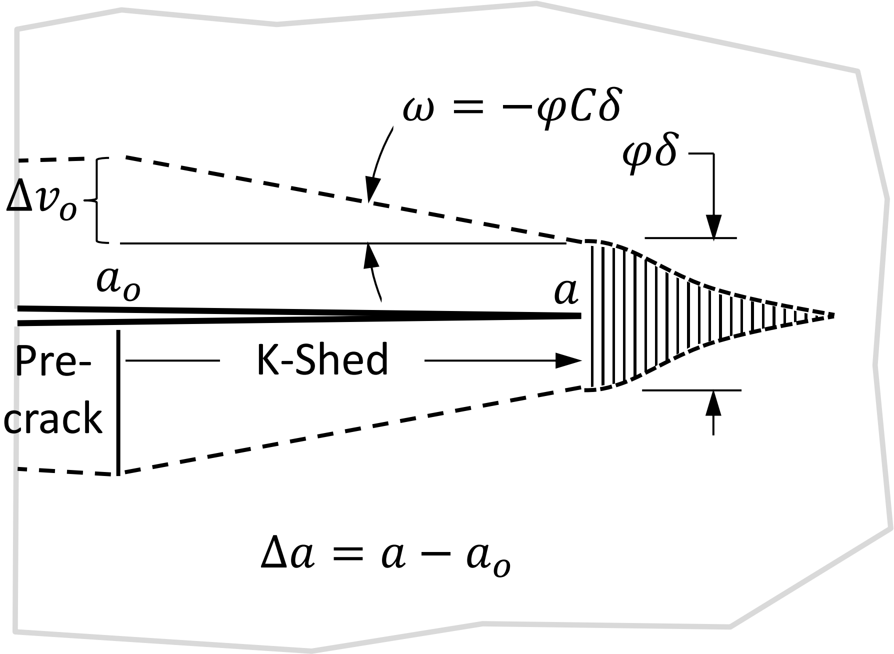
A Further Normalization, $\epsilon_{c\delta}$



Cδ, or $(C\delta)_{eq}$ are related to the wake angle, ω, and thus represent an additional displacement, Δv_o at a_o beyond the steady state (ω=0) condition. The retardation effect would be expected to correlate with the ratio Δv_o to the corresponding elastic displacement, v_{oe}

$$\frac{\Delta v_o}{v_{oe}} \propto \epsilon_{c\delta} = \frac{(C\delta)_{eq} E\sqrt{\Delta a}}{\gamma K} = \frac{\left(K_o{}^2 - K^2\right)}{2\gamma\sigma_y K\sqrt{\Delta a}}$$

where

$$\gamma\left(\frac{a}{W}, \Delta a\right) = \sqrt{\frac{\pi}{8}}\,\frac{vE}{K_{max}\sqrt{\Delta a}}$$

Expression for γ includes correction of error in original presentation

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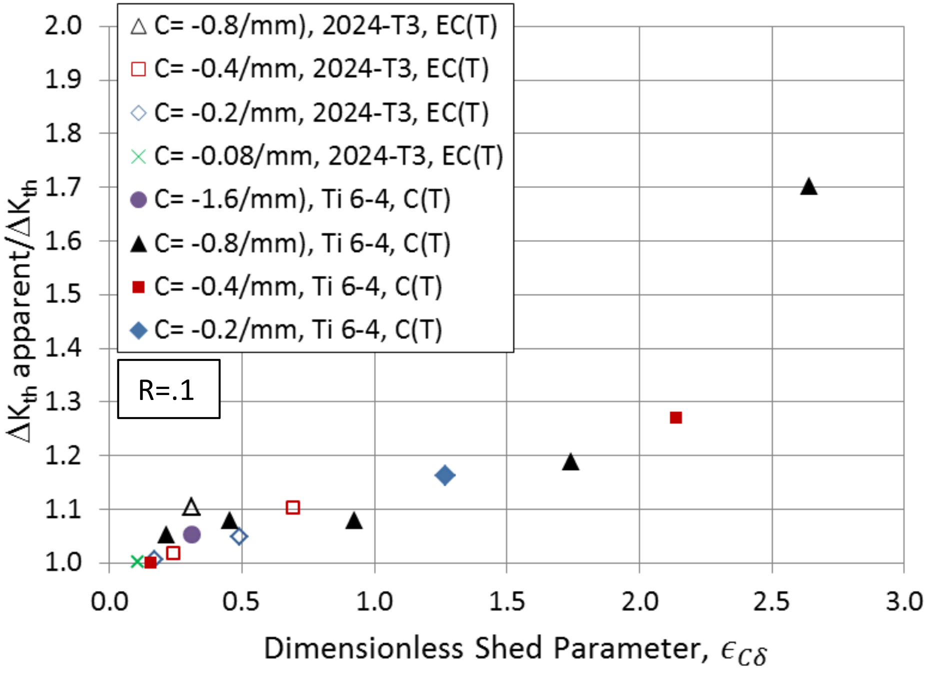
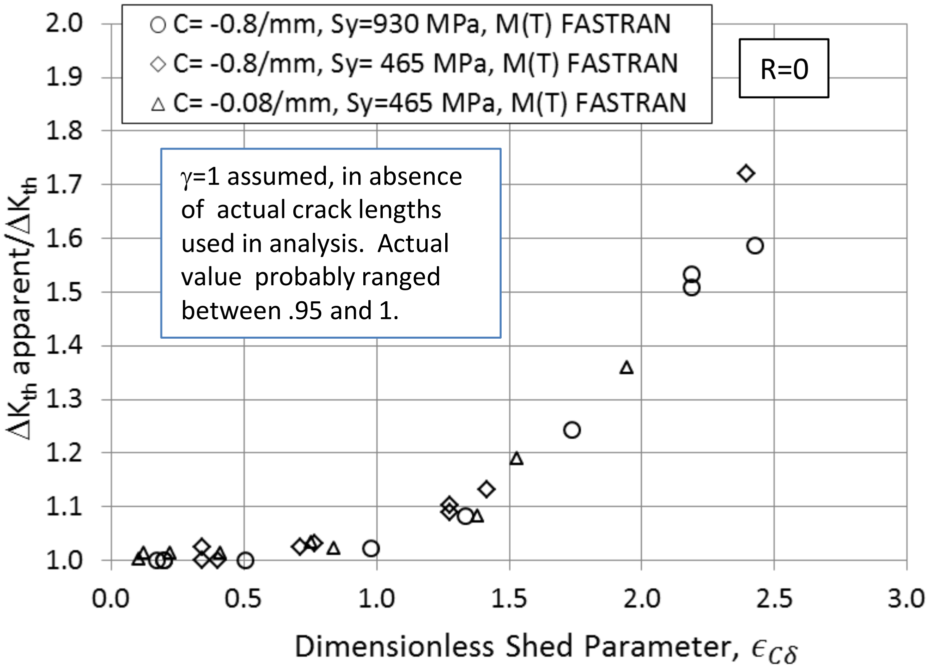
Correlation With $\epsilon_{c\delta}$





γ=1 assumed, in absence of actual crack lengths used in analysis. Actual value probably ranged between .95 and 1.

- $\epsilon_{C\delta}$ collapses test data and FASTRAN simulations
- Imposing $\epsilon_{C\delta} \leq .25$ restricts artifact to about 5%
  - Based on FASTRAN simulations, this may be conservative

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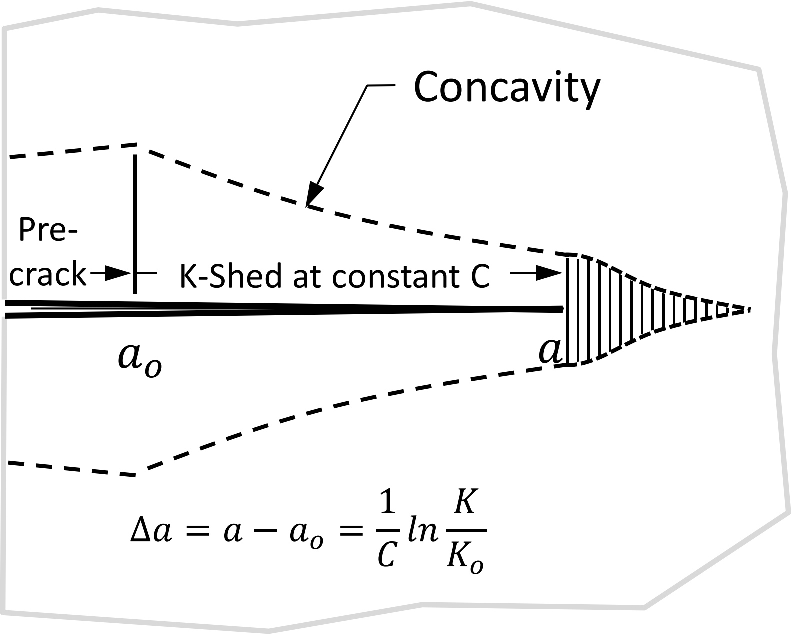
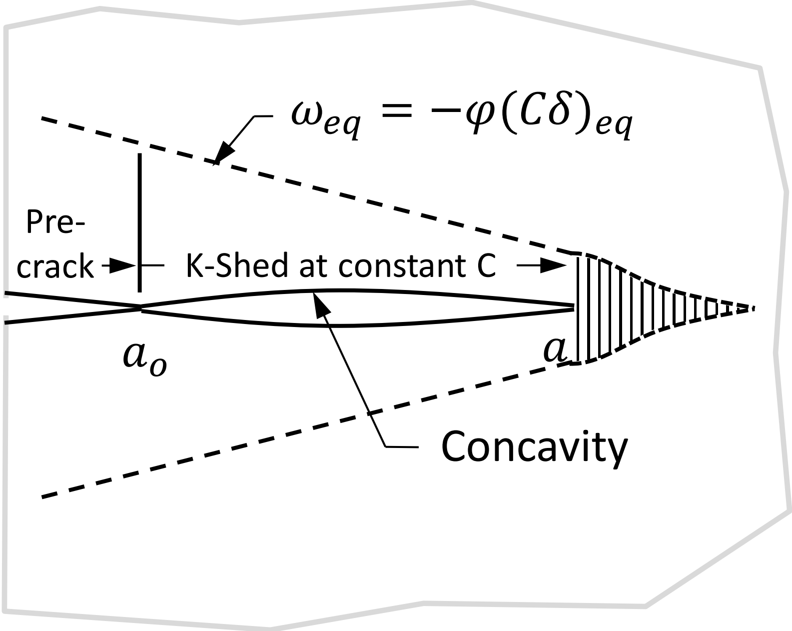
What About Remote Closure?

It results from the concave plastic wedge left by constant C shedding!



$$\Delta a = a - a_o = \frac{1}{C} ln \frac{K}{K_o}$$



$$\omega_{eq} = -\varphi(C\delta)_{eq}$$

Elastic crack **will not** conform to external concavity as shown here

Instead, **concavity will be forced internal** (View shows elastic- plastic boundary fixed along ω_{eq})

- Forcing $\frac{d^2\delta}{da^2} = 0$ (shedding at constant Cδ) eliminates concavity!

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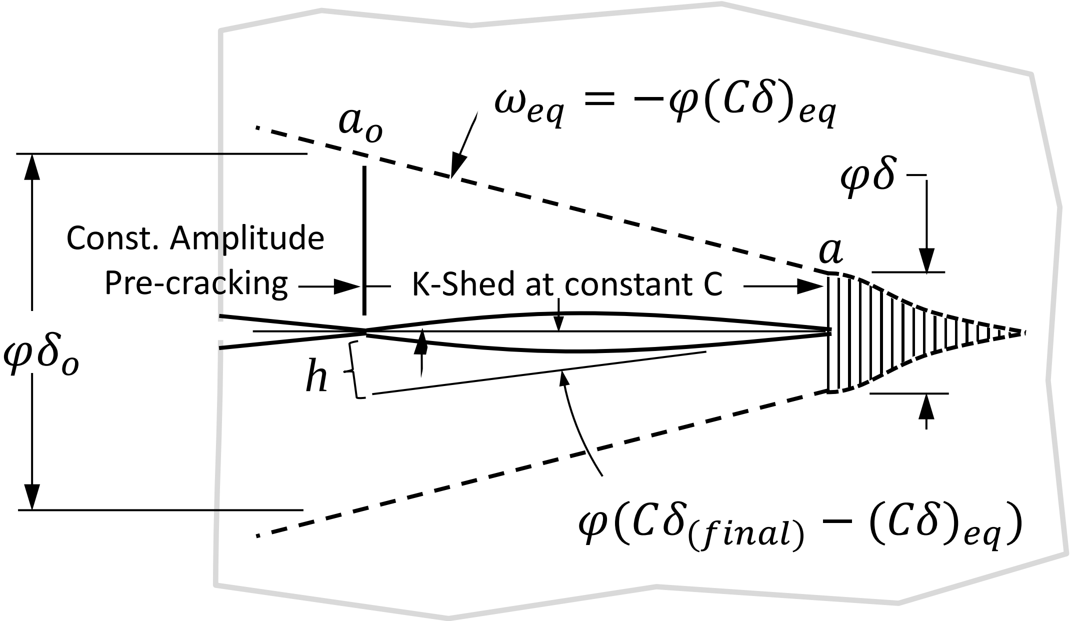
A Concavity Parameter



Concavity parameter, ϵ_{rc} based on the ratio of the “plastic asperity” size,

$$h = \varphi\left(C\delta - (C\delta)_{eq}\right)(a - a_o)$$

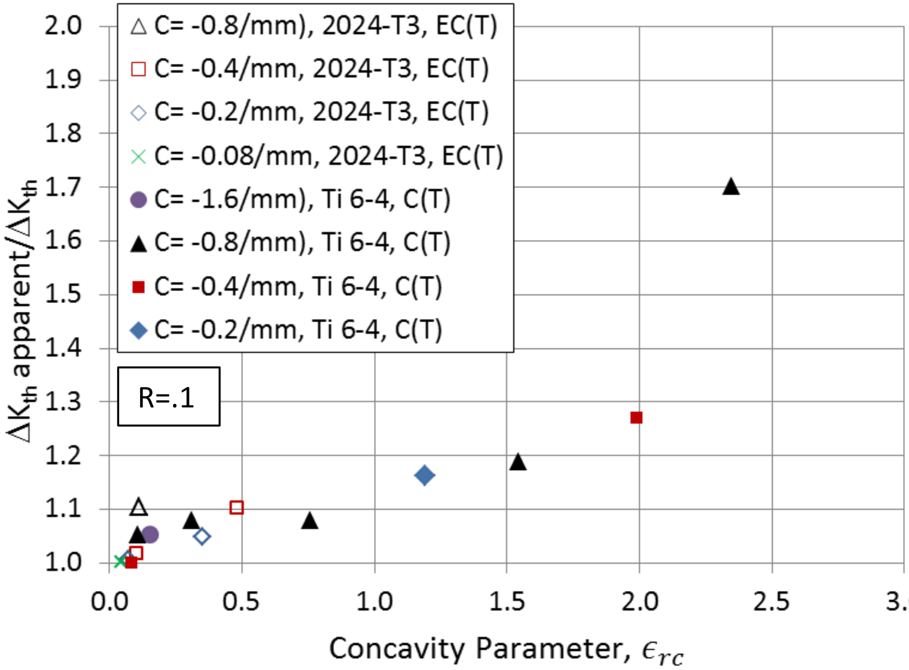
to the local elastic crack opening at a_o,

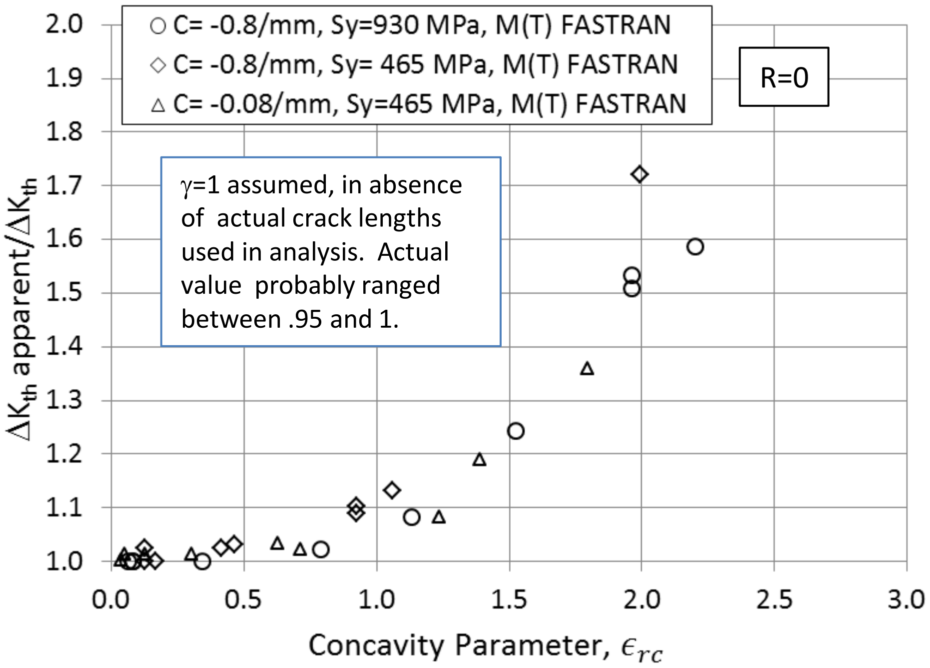
$$\frac{h}{v_{oe}} \propto \epsilon_{rc} = \frac{E\left(C\delta - (C\delta)_{eq}\right)\sqrt{\Delta a}}{\gamma K_{max}}$$

$$\epsilon_{rc} = \frac{K_{max}\sqrt{C\, ln\frac{K}{K_o}}}{\gamma\sigma_y}\left[\left(\frac{K}{K_o}\right)^2 + \frac{1 - \left(\frac{K}{K_o}\right)^2}{2\ln\left(\frac{K}{K_o}\right)}\right]$$

(for constant C)

Correlation With Concavity Parameter





γ=1 assumed, in absence of actual crack lengths used in analysis. Actual value probably ranged between .95 and 1.

- ϵ_{rc} curves appear very similar to $\epsilon_{C\delta}$ curves
  - Parameters merge as $C\delta << (C\delta)_{eq}$
- Note that ϵ_{rc}→0 for constant $C\delta$ shed, but $\epsilon_{C\delta}$ remains

FASTRAN results based on McClung (2000)
Threshold ratio based on ΔKeff /min ΔKeff
at applied ΔK of 5.5 Mpa

Pause for Discussion

- Based on the above development, the artifact is primarily associated with $\epsilon_{C\delta}$ (K-shed rate), and that concavity/remote closure may make up a portion of that artifact, depending on the manner in which K is shed, but does little to change its magnitude.
  - Imposing $\epsilon_{C\delta} \leq .25$ restricts artifact to about 5% (this may be conservative)
  - K-shedding at constant Cδ eliminates remote closure, but artifact remains per $\epsilon_{C\delta}$
  - K-shedding at constant Cδ can reduce test time, and thus may be useful
- However, another way to avoid shed artifact is to use a load shed scheme or test specimen that limits contact between the remote regions of the plastic wedge (positive R only?)
  - Wu (1995), proposed shedding at constant Crack Mouth Opening Displacement (CMOD)
  - The FBH specimen sheds K while testing at constant load, thus with a constantly increasing CMOD as the crack grows

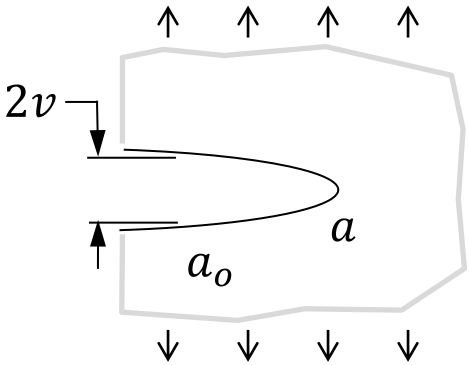
Shed Artifact Control by Compliance (SACC)

Defining the local compliance

$$Q(a_o) = \frac{2v(a_o)}{\sigma}$$

It is evident that to keep the displacement from decreasing as the crack grows (to avoid compressing the plastic wedge), we must enforce

$$\frac{d}{da}(Q\sigma) \geq 0 \;\; \rightarrow \;\; \frac{1}{\sigma}\frac{d\sigma}{da} \geq -\frac{1}{Q}\frac{dQ}{da}$$



a_o location represents the beginning of K-shed as described earlier

That is, to avoid shed artifact using SACC, the **load** shed rate must be restricted based on compliance characteristics, which are specimen geometry dependent. Q and dQ/da are always positive for K>0, suggesting that a finite load shed rate is permissible for any specimen.

- The FBH specimen tested at *constant* load always satisfies SACC!

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SACC Continued

For convenience, this criterion can be re-expressed in terms of the K-shed rate for an arbitrary specimen of K-solution

$$K = \sigma\sqrt{\pi a}\,\beta$$

The K-shed rate can be expressed as

$$C = \frac{1}{K}\frac{dK}{da} = \frac{1}{2a} + \frac{1}{\beta}\frac{d\beta}{da} + \frac{1}{\sigma}\frac{d\sigma}{da}$$

By imposing the SACC restriction $\frac{1}{\sigma}\frac{d\sigma}{da} \geq -\frac{1}{Q}\frac{dQ}{da}$ on the load shed rate we obtain the permissible K-shed rate

$$C \geq C_{SACC} = \frac{1}{2a} + \frac{1}{\beta}\frac{d\beta}{da} - \frac{1}{Q}\frac{dQ}{da}$$

Summary

- FBH testing provides high precision, reproducible crack growth threshold data at >100 Hz
  - Small specimen size (.63 DIA x 1.75 blank)
  - Uniform crack closure state across crack front (no free surface intersection)
  - Crack front shape precisely known (circular & self-centering)
  - Stiff specimen loading set-up; enables high testing at high frequency
  - Favorable natural K-shed behavior allow threshold testing at constant load, and mitigates test artifact associated with shedding

- Shed parameters for conventional specimens also proposed