Through the Tensile Field.. An Investigation on the Residual Stress Field of a Cold Worked Hole

AFGROW Users' Conference

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The Outline

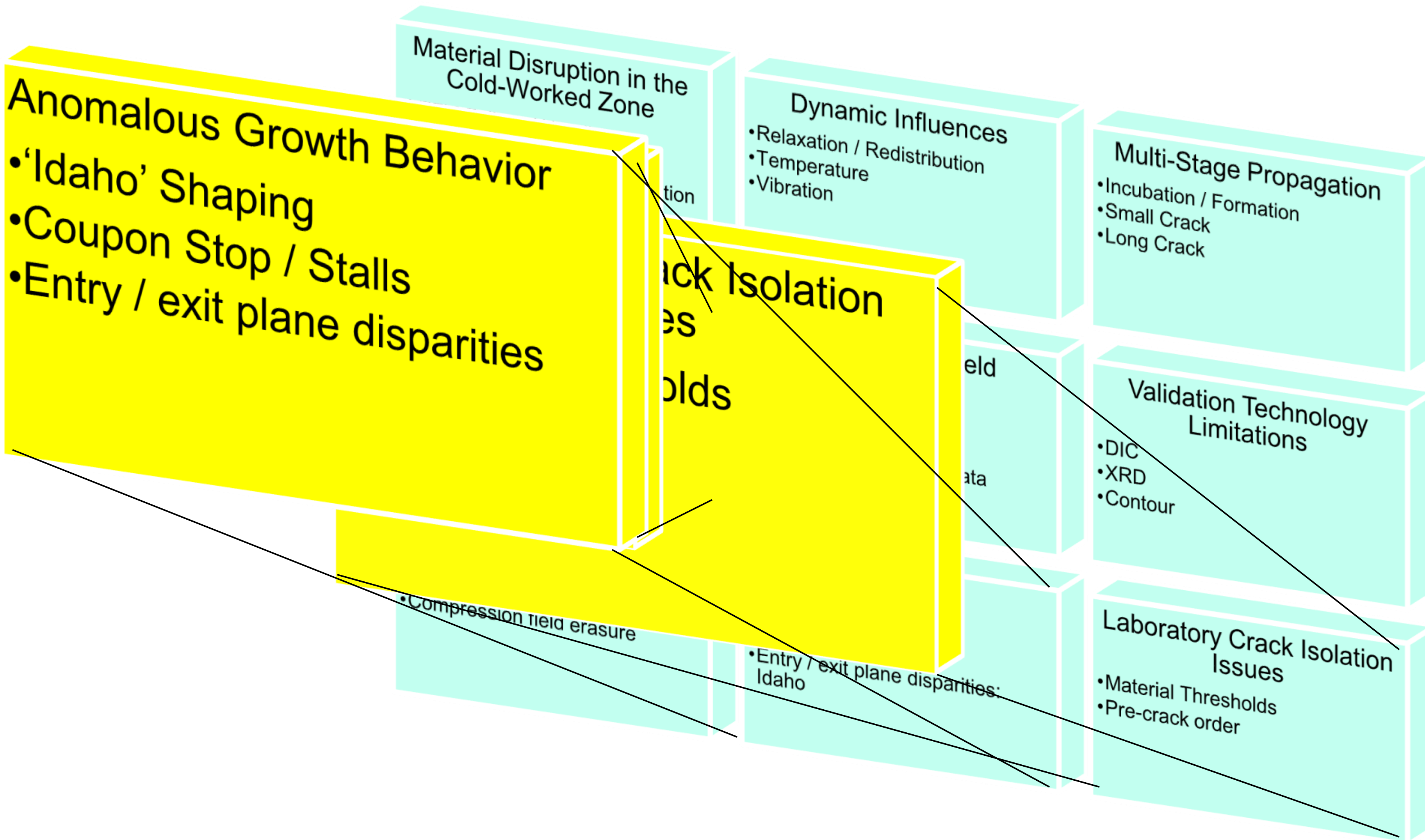
The Rationale to Reverse

Characterization Data and Beta Solutions

Fatigue Life Results

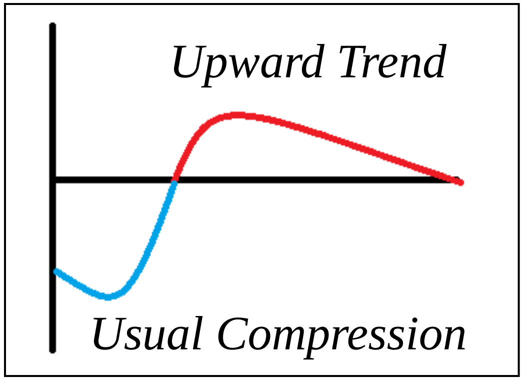
Residual ‘K’ Results

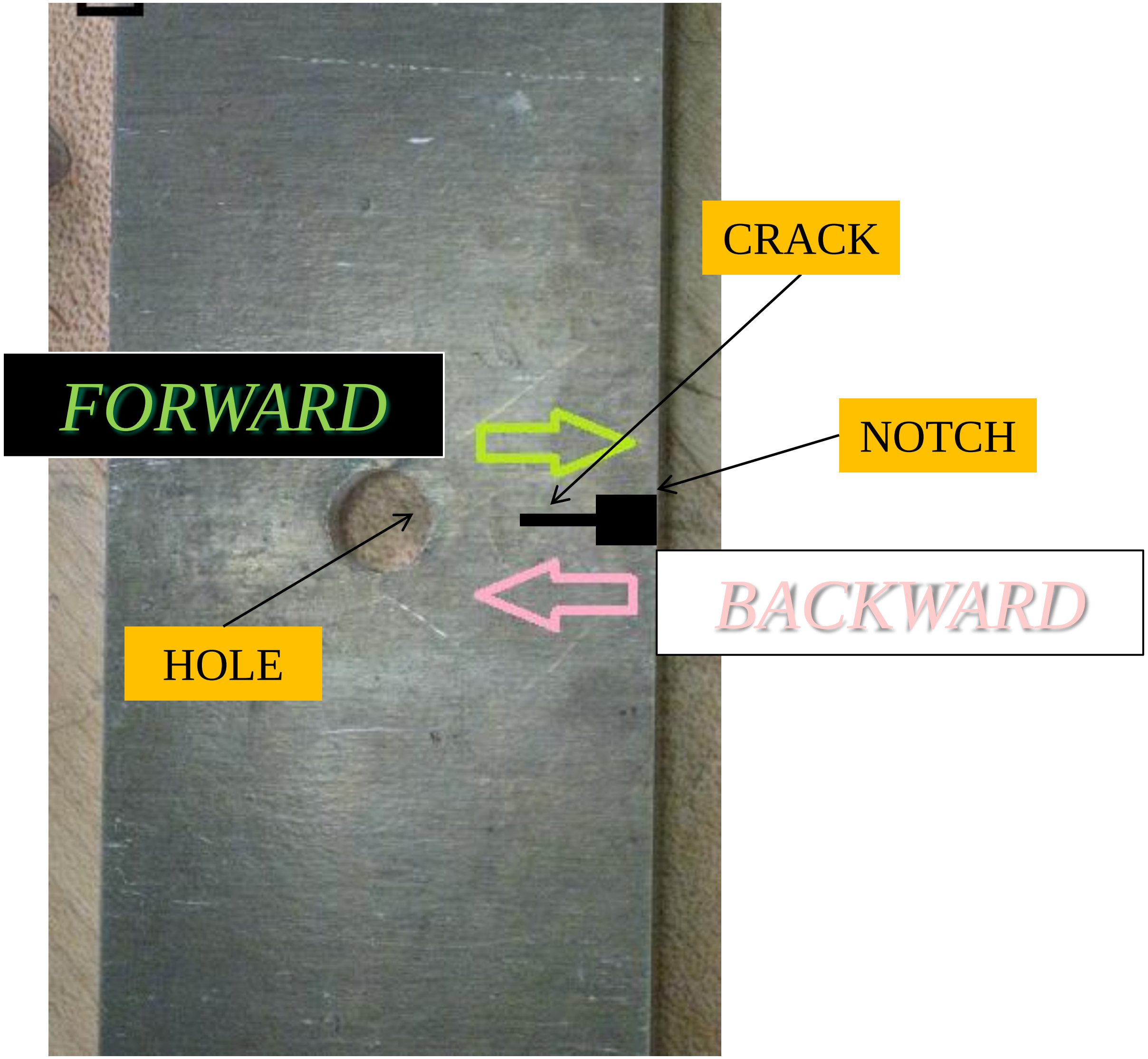
Motivation:
The Cold-Working Risk Matrix



The Motivation & Terminology

***Hypothesis**: The residual stress of a cold-worked hole can be verified by growing a crack through the Cx field backwards then by reversing the geometry solution to generate a residual ‘K’ parameter*



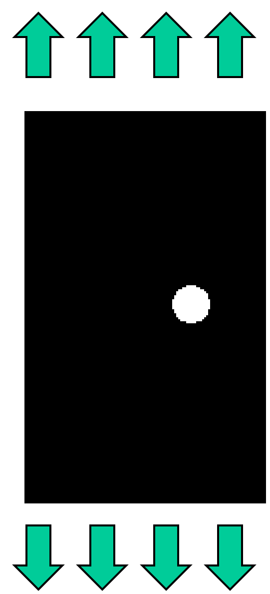


Reversing the Residual Stress

Remote Equivalent 'Residual' Stress

β (backward)

β (reverse)

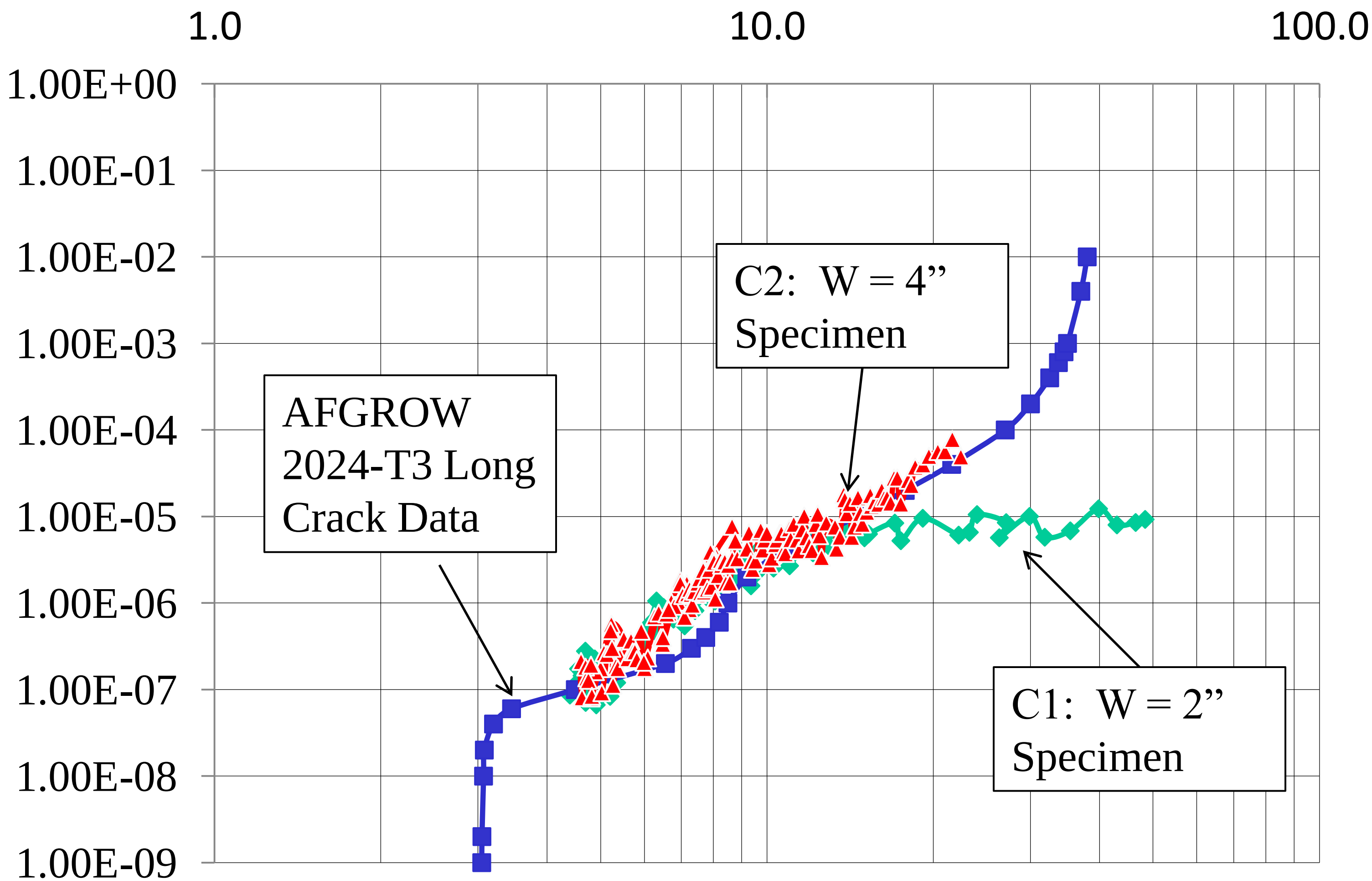


Residual K Backward

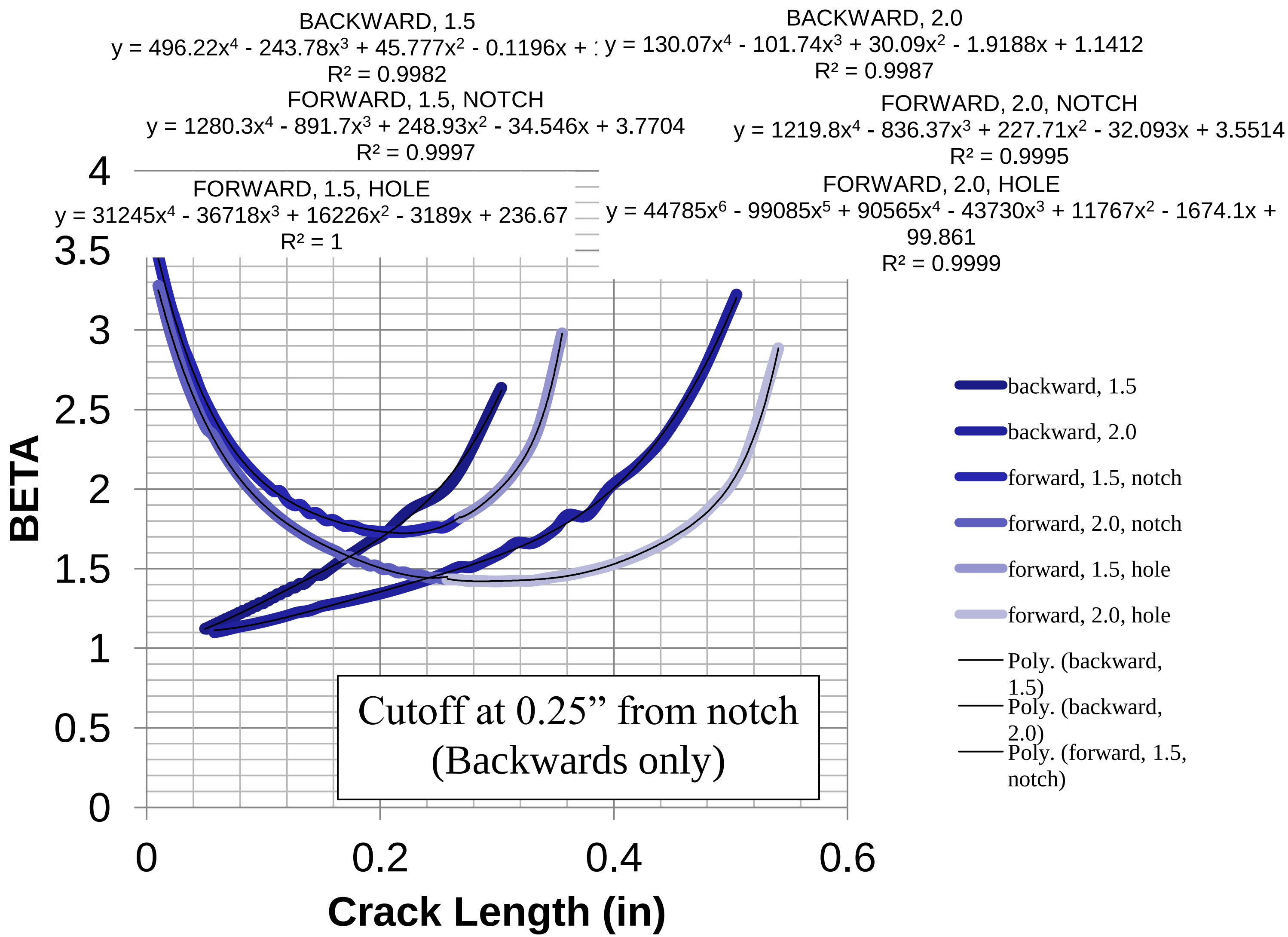
Residual K Forward

Characterization Results: Al-2024-T351 (Al-Clad)

da/dN (in / cycle) vs ΔK (ksi*sqrt(in))



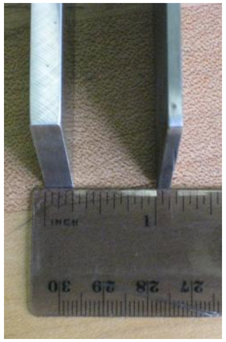
Beta Solutions: AFGROW®



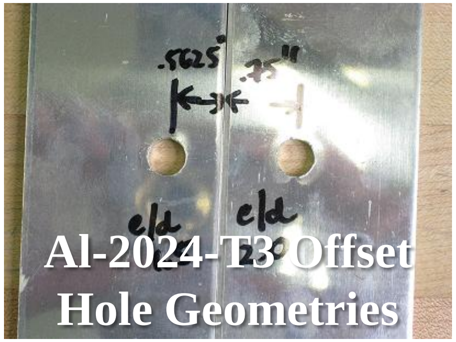
Testing Information

- Loading:
  - 15 ksi, R = 0.0
  - Constant Amplitude & “Constant K (Test)”
- Al-2024-T3 (Al-Clad), 1/8”, e/d = 1.5, 2
- 3/8” Hole (FTI:CBM-12-N-1-40-V1)

Constant Growth Rate !!!



AL-2024-T3 Center Hole Geometry



Al-2024-T3 Offset Hole Geometries

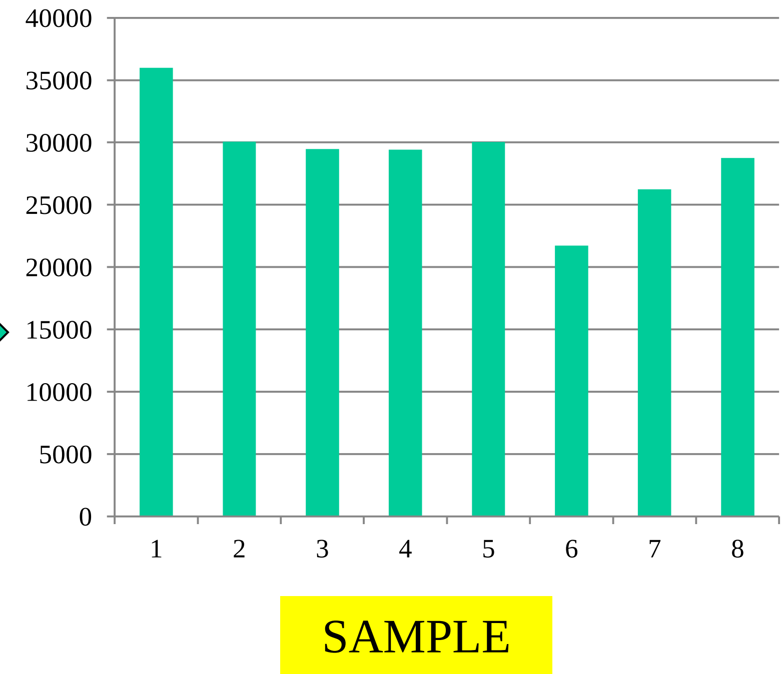
IN PROGRESS

Results from Test Data

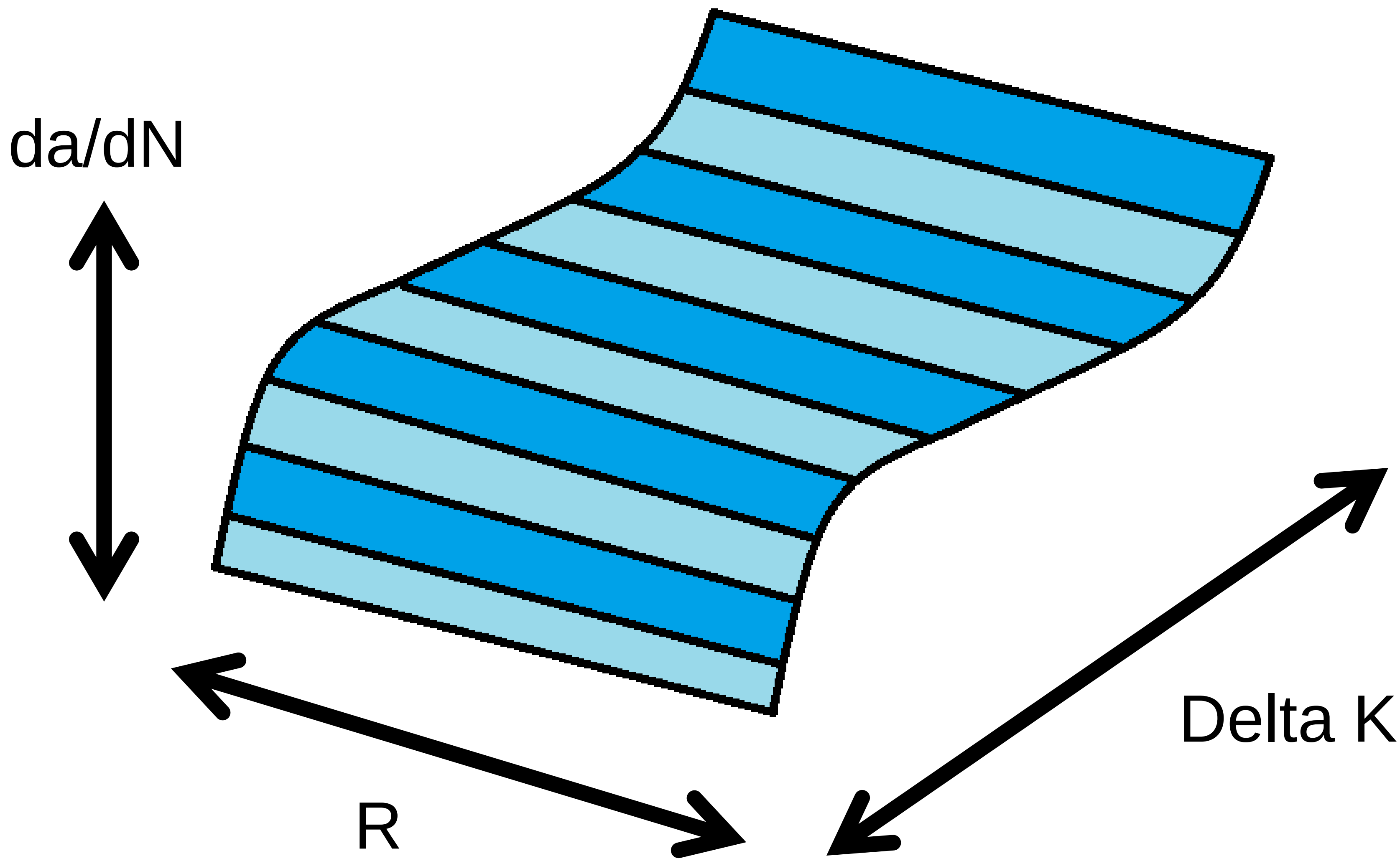
Notch	*Init. to ~0.15”*	*Crack Growth (CG)*		*Cont. Damage Init. & Failure*

- More predictable results:
  - *CG Life* of cold worked hole < *CG Life* of the baseline
  - *CG Life* of 1.5 < CG Life of 2.0 (Baseline & Cx)
- Less obvious result:
  - *Total Life of Each Coupon is ~ Equal!*

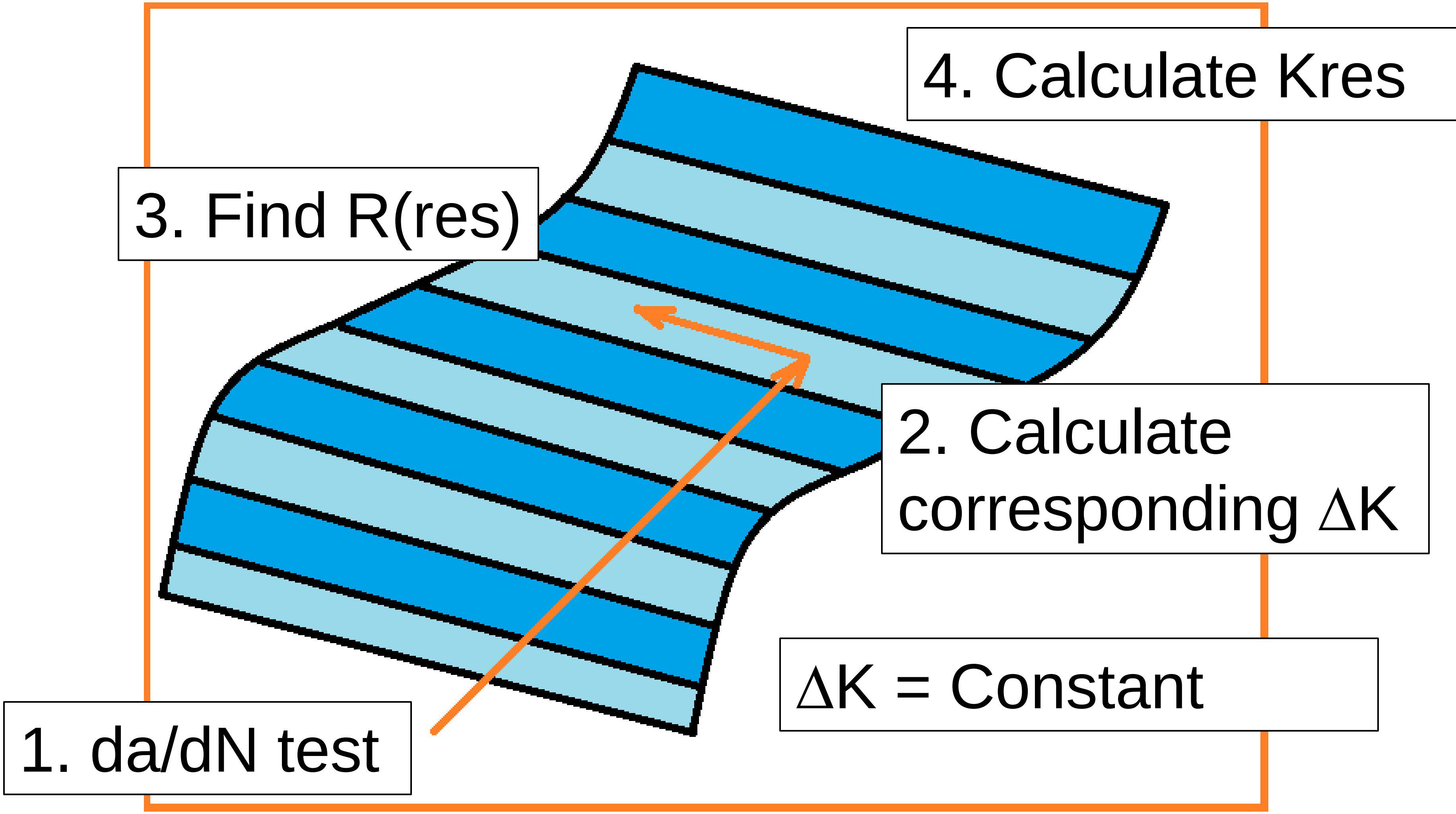
Anonymous & Assorted Constant Amplitude Results (e/d = 1.5 & 2.0)



Our FCG Curve in 3-Space

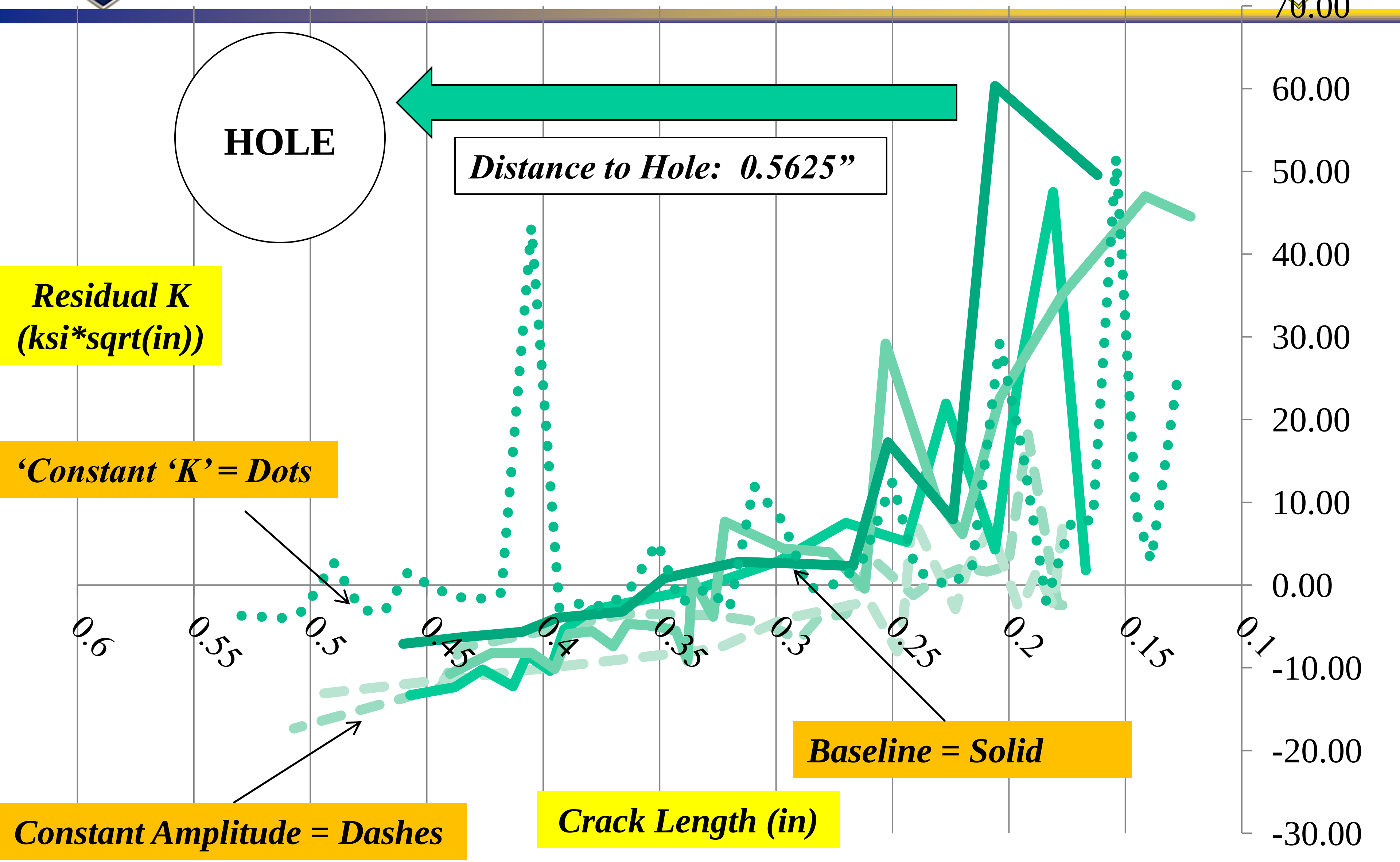


'Classic' Residual K

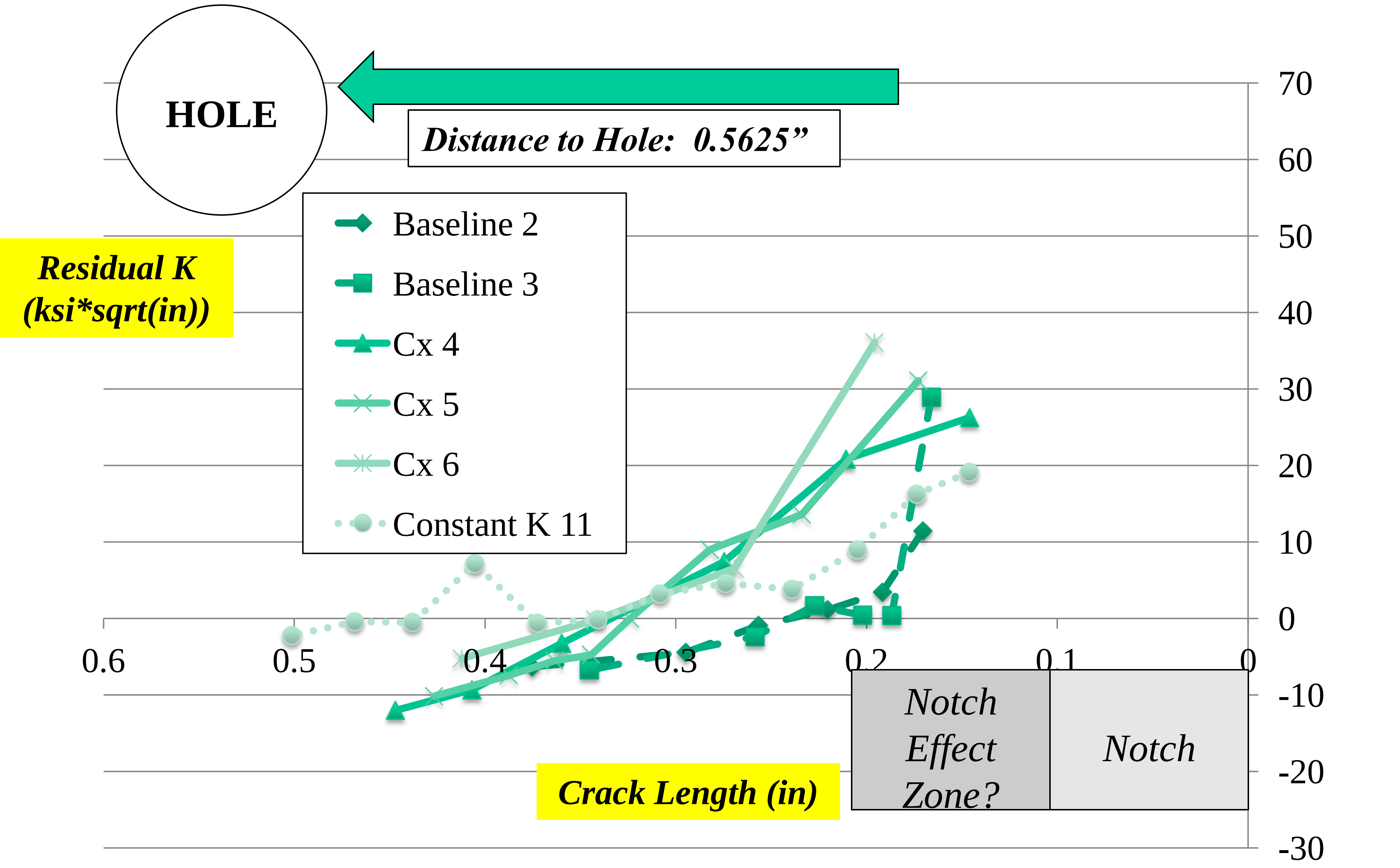


Relies on Linear Superposition of K's

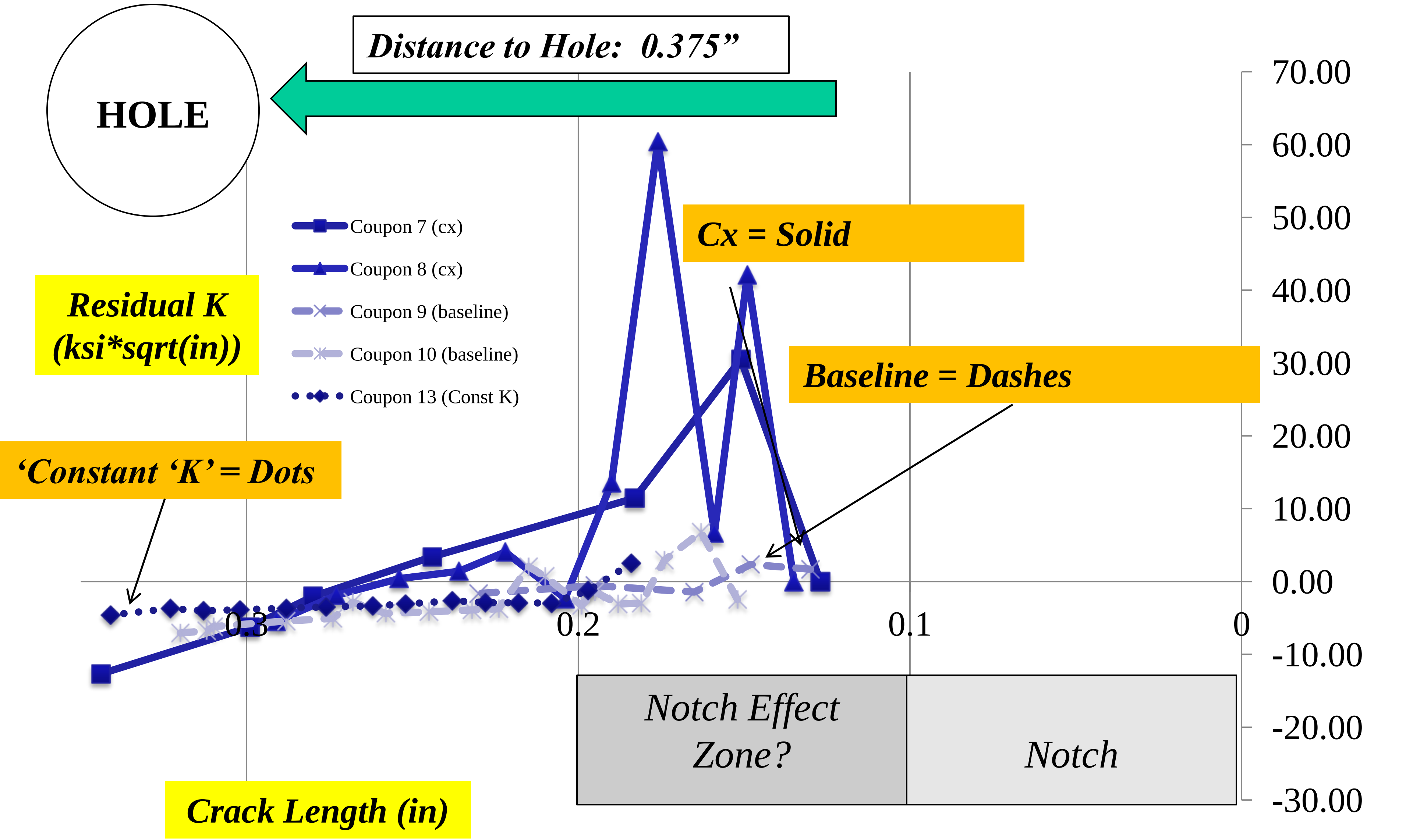
‘Classic’ Residual K Results



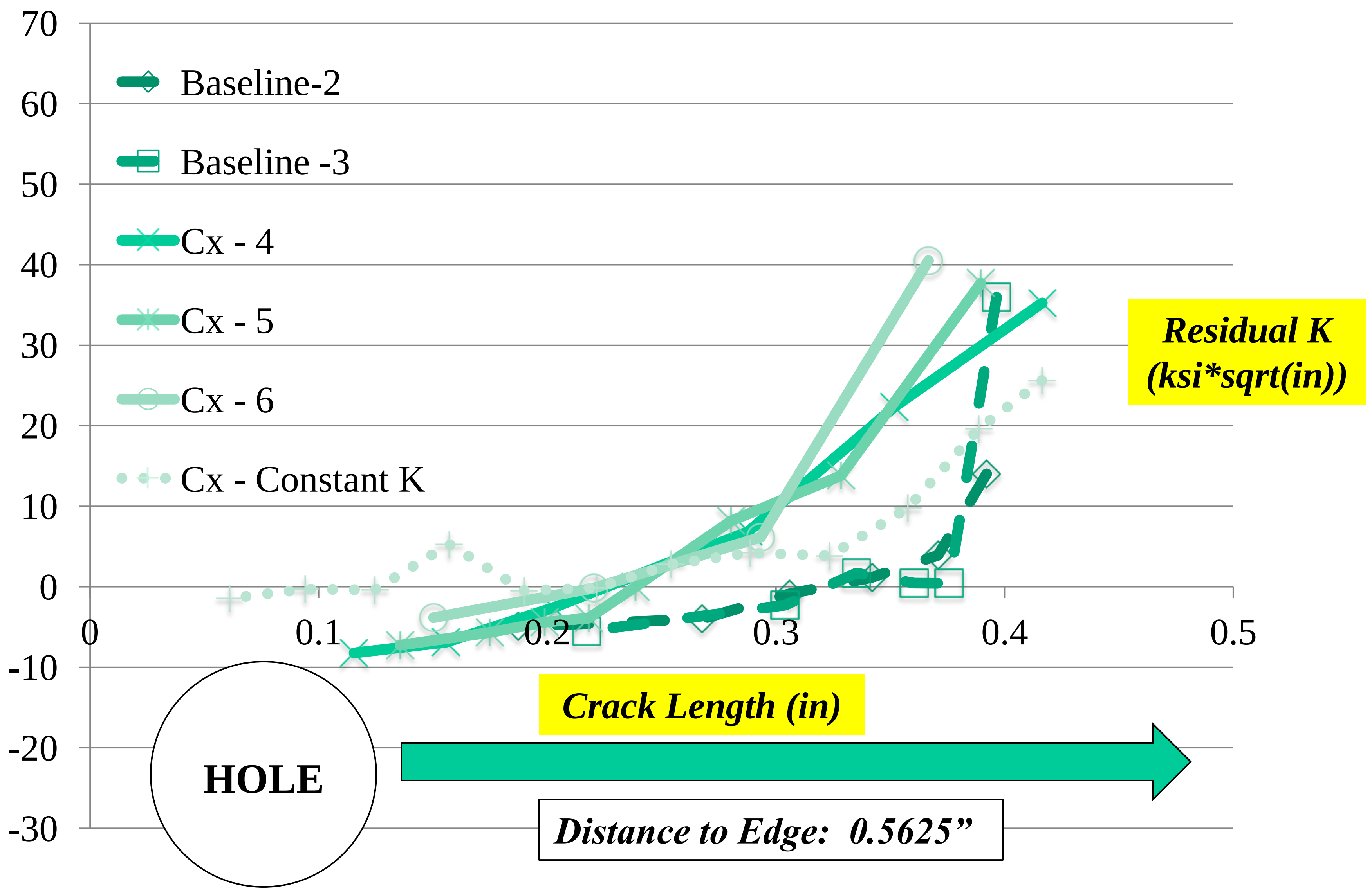
e/d = 2.0: *Same Data* Averaged for 5 Increments



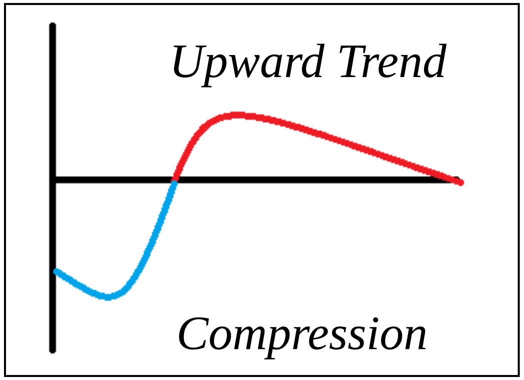
‘Classic’ Residual Stress Results

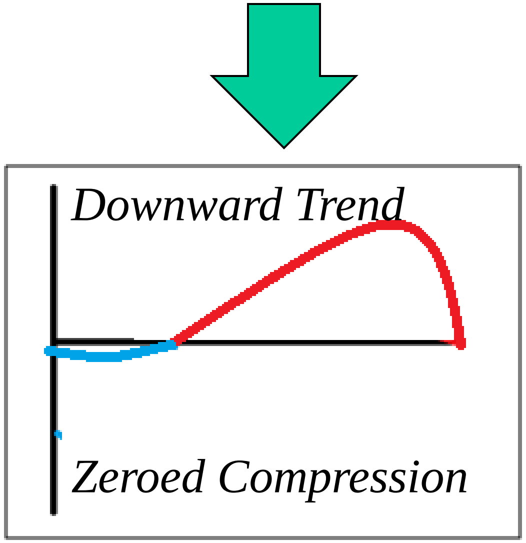


For Completion: *Forward* Residual K Field



Home Stretch





Conclusions

The compressive field is significantly reduced after the tensile field is cracked through

The total life of the coupons was unchanged by cold working with the crack growing in the continuing damage scenario

Huge variability is present in the tensile region of the residual stress field, but is most likely caused by the notching of a cold-worked specimen

Constant K results point to stress dependencies in the residual stress field (further replicates required)

Suggestions for Future Work:
Things you may or may not want to do

- Use the tensile residual stress field to predict the compressive residual stress field
  - Can you destroy it in enough ways to assemble a residual stress profile?
- Testing the residual stress superposition technique:
  - Does a spectrum dependency occur?
- Equating FOD to residual stress
  - Do you always see a significant variability in Kres?
- Other usual suspects
  - More holes, thicker plates, larger plates, material misorientation, mishapen/square holes, front and back side cold-working

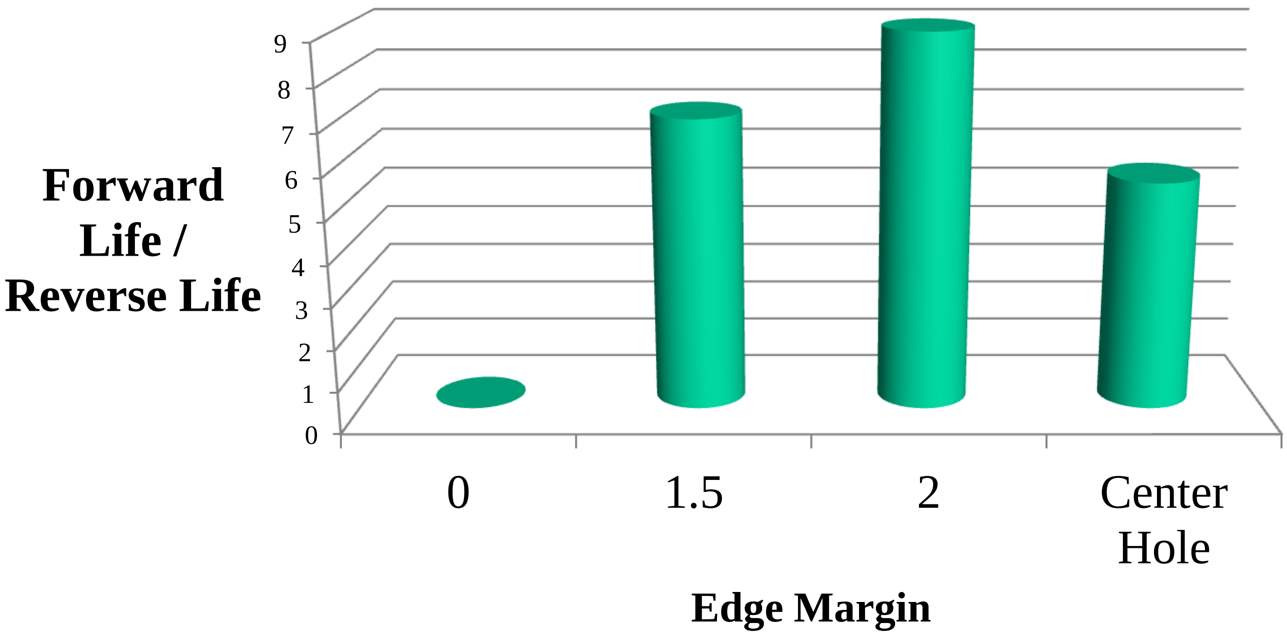
"Interest does not always equate to time."
-Ted Nicholas

Done.

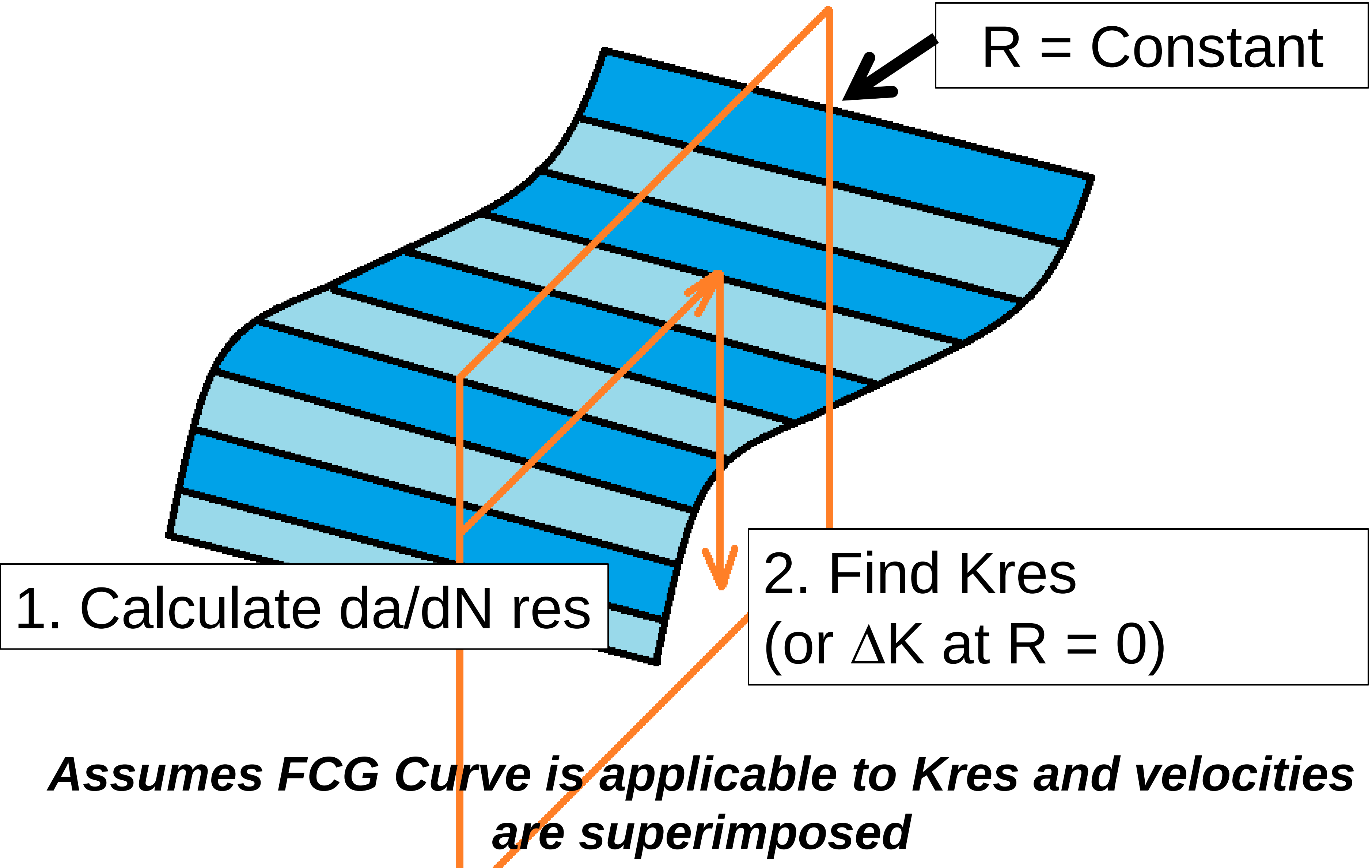
Backup Slides

A Quick Look at the Geometry

– What edge margin gives the most significant jump in fatigue life?
  - 15 ksi, R = 0.0, Constant Amplitude
  - 0.05” Through Crack

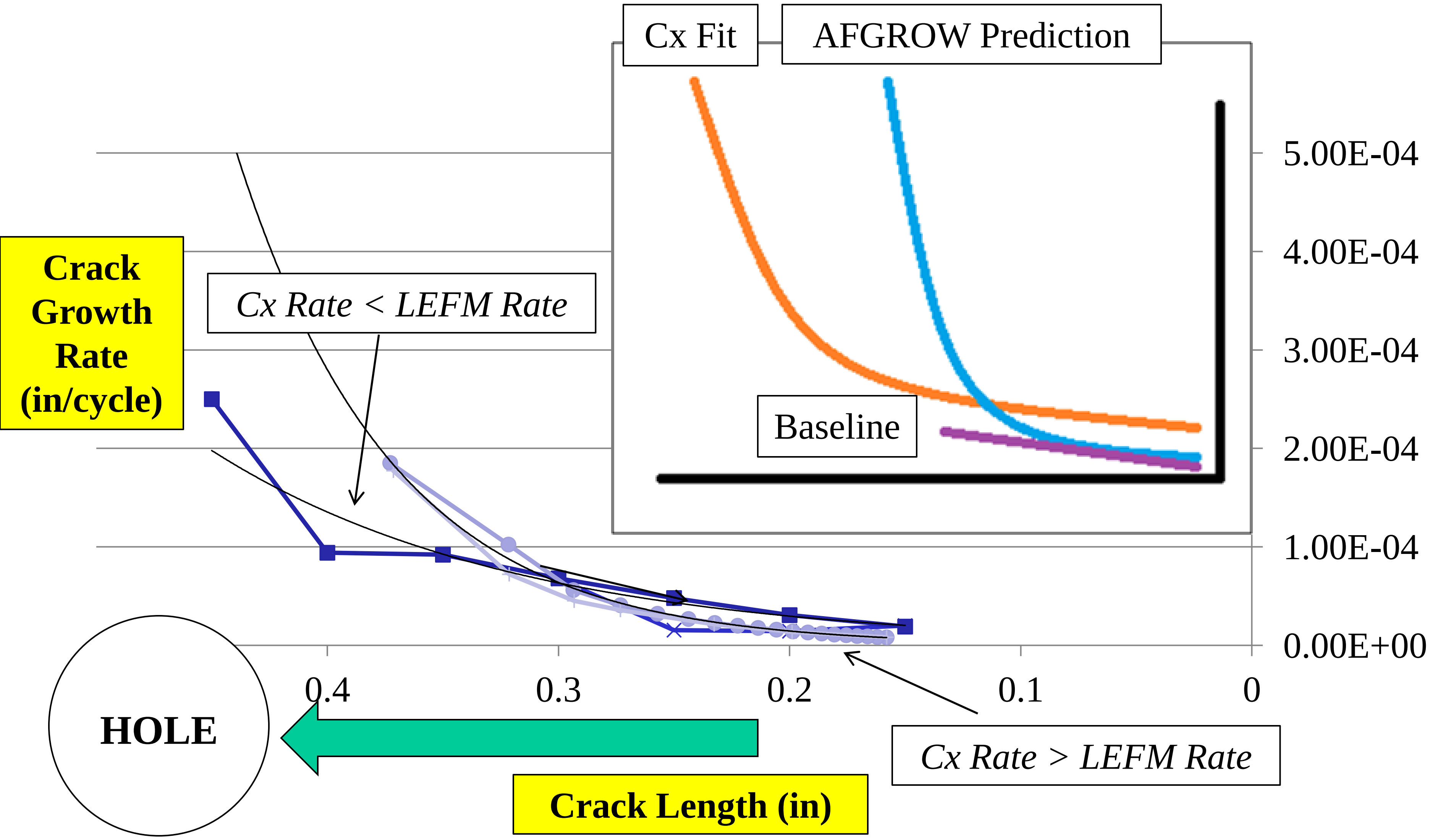


'Subtraction' Method

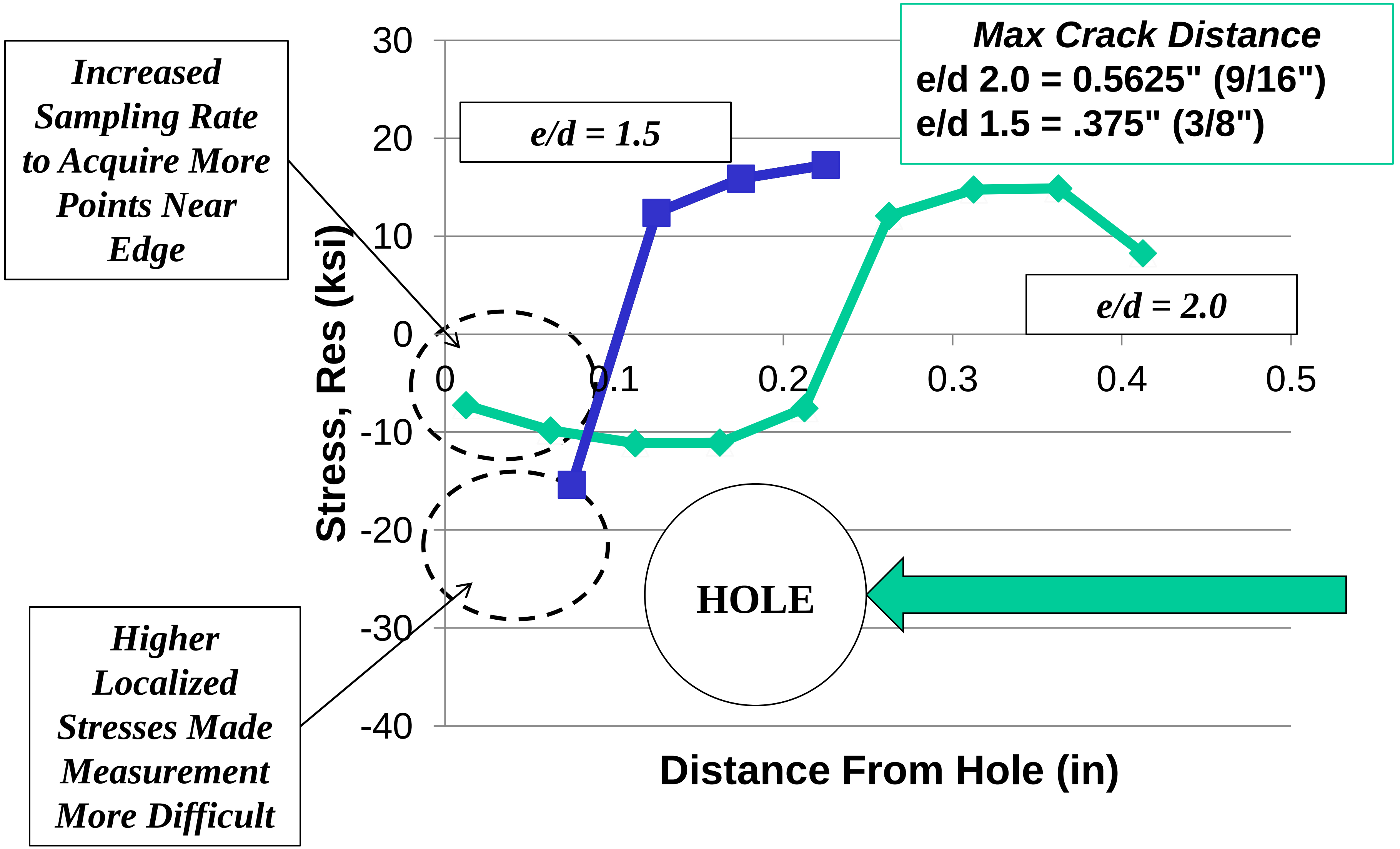


Assumes FCG Curve is applicable to Kres and velocities are superimposed

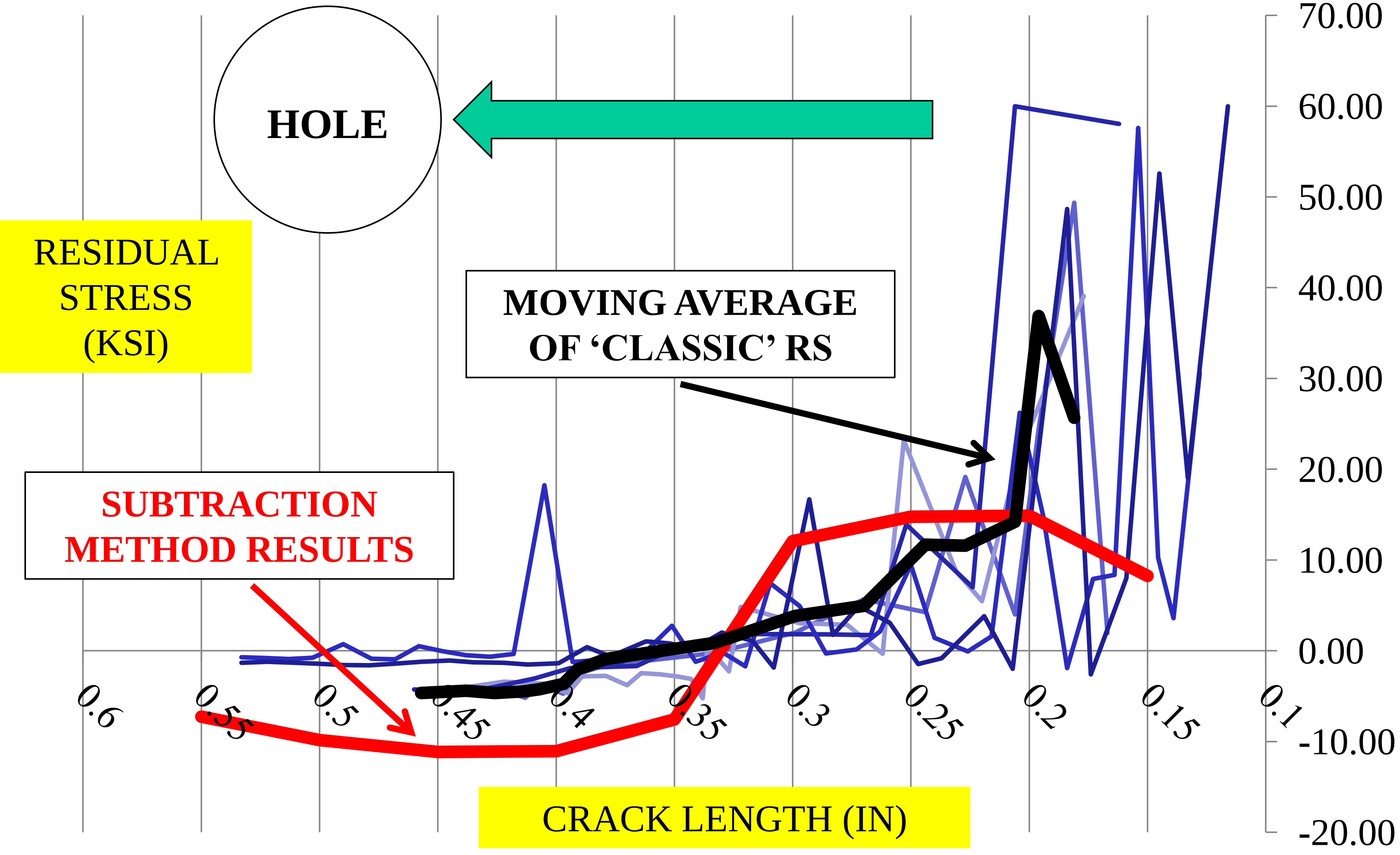
Subtraction Method:
A Look at the Growth Rate Behavior



Subtraction Method
σ (res)

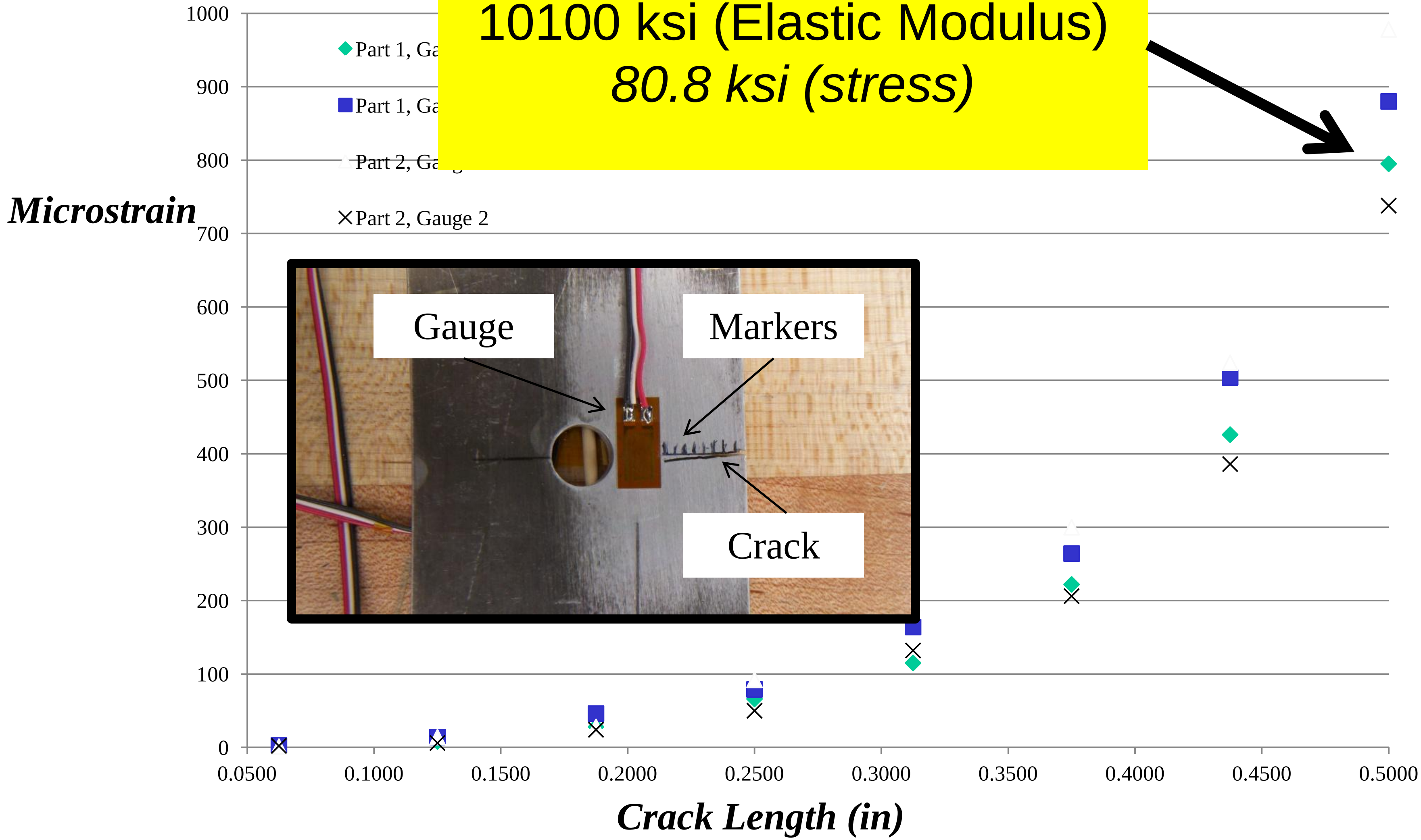


Residual Stress Plot Overlay of e/d = 2.0



Which method is more right?
… checking the strain relief

800 με (strain)
10100 ksi (Elastic Modulus)
80.8 ksi (stress)



How is each method implemented in a prediction?

**Classic:
Residual 'K' vs. 'c' profile during LEFM run**

Similitude allows for a master curve

R = (Kmin +/- Kres) / (Kmax +/- Kres)

**Subtraction:
Residual 'da/dN' vs 'c' table**

Tables will need to be developed for differing load scenarios

da/dN = da/dN (LEFM) + da/dN (res)

Background: The Rational to Reverse

- Forward Cracking
  - Low-load threshold (= Load Bumping)
  - ‘Strange’ crack shapes
  - Tensile field erasure
- Reverse Cracking
  - Peak compression not interfered by notch
  - Free to run any loading condition to get growth
  - Tensile effect is present

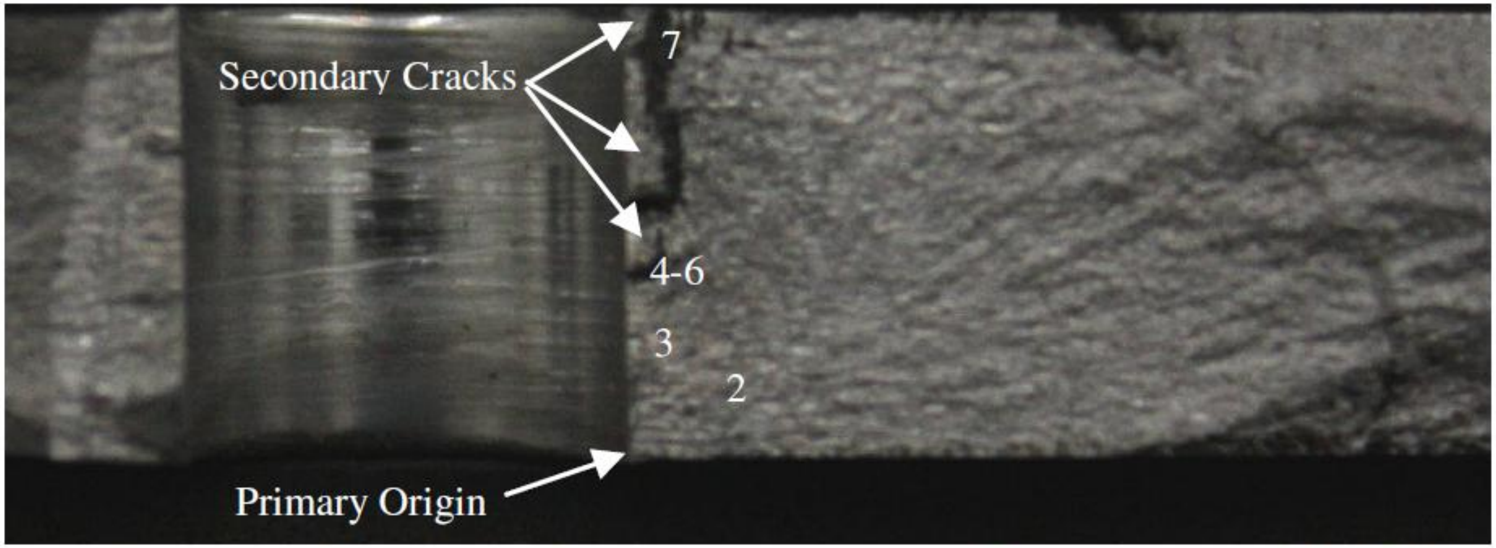


Figure 1. Coupon CX07 (AKA 1D07) Optical macro fracture view of specimen CX-07. Numbers indicate regions where subsequent images were taken using SEM.

Constant Amplitude Results: 15 ksi, R = 0, 2024-T3 (Al-Clad)

Life between c = 0.15” and Failure at the Hole: ***Pre-crack = 15 ksi***

$N_{Cx} > N_{baseline}$; $N_{Cx,\ 2.0} > N_{Cx,\ 1.5}$; $N_{baseline,\ 2.0} > N_{baseline,\ 1.5}$

Total Life: $N_{Cx,\ 2.0} = N_{baseline,\ 2.0} = N_{Cx,\ 1.5} = N_{baseline,\ 1.5}$ (approx)

TEST MATRIX **R = 0.0**

All loads in kips!

Trial	Description	e/D	σ (ksi)	Pmax	Pmid	Pamp	Cycles to To .15"	Right Cycles to Failure	Left Cycles to Failure	Total Cycles to Failure
1	Test Dummy	2.0	24	6	3	3				
2	Baseline	2.0	15	3.75	1.875	1.875	12000	9200	*DNR*	*21200*
3	Baseline	2.0	15	3.75	1.875	1.875	9500	12500	14000	36000
4	Cx	2.0	15	3.75	1.875	1.875	10500	6750	12810	30060
5	Cx	2.0	15	3.75	1.875	1.875	11000	6550	11908	29458
6	Cx	2.0	15	3.75	1.875	1.875	12700	4950	11766	29416
7	Cx	1.5	15	3.75	1.875	1.875	8000	2500	19535	30035
8	Cx	1.5	15	3.75	1.875	1.875	5500	2700	13525	21725
9	Baseline	1.5	15	3.75	1.875	1.875	14500	3500	8233	26233
10	Baseline	1.5	15	3.75	1.875	1.875	12500	4800	11459	28759

Test Matrix: FYI

Trial	Description	e/D	σ (ksi)
1	Casualty	2.0	24
2	Baseline	2.0	15
3	Baseline	2.0	15
4	Cx	2.0	15
5	Cx	2.0	15
6	Cx	2.0	15
7	Cx	1.5	15
8	Cx	1.5	15
9	Baseline	1.5	15
10	Baseline	1.5	15
11	Cx (Const K)	2.0	15
12	Cx (Const K)	2.0	15
13	Cx (Const K)	1.5	15
14	Cx (Const K)	1.5	15
15	Center Hole(IP)	2.67	15
16	Center Hole(IP)	2.67	15
17	Forward (Const K)	1.5	15
18	Forward (Const K)	2.0	15
19	Forward (Const K)	2.0	15

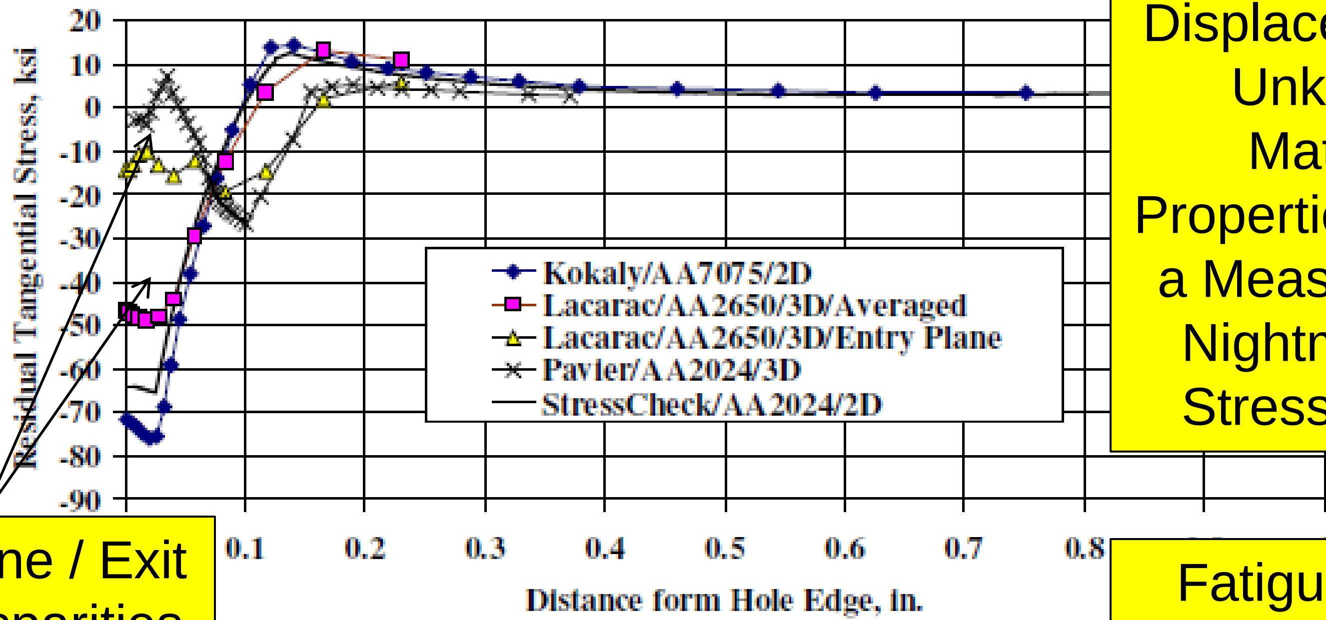
Background:
The Rational to Reverse

- *Back-Cracking*
  - Another perspective on Cx holes
  - Peak of the R.S. field will not be interfered by notch
  - Tensile effect is fully present
  - Free to run at any operational load
  - The Intangibles
- *Downsides*
  - The test gets exciting at the peak of the R.S. compressive zone
  - Flipping Sigma (Res) to calculate K (Res) / tensile relief may be problematic
  - Elastic response will change residual stress field*

The Motivation

How do you account for the fatigue life benefit of a cold worked hole?

Small Displacements & Unknown Material Properties Create a Measurement Nightmare for Stress Fields!



. Comparison of Finite Element Simulations from S

Entry Plane / Exit Plane Disparities Make a Conclusive RS Field

Fatigue Crack Growth Models Compound Your Problems!

Method #2: Subtraction

$$da/dN_{res} = da/dN_{test} - da/dN_{LEFM/baseline}$$

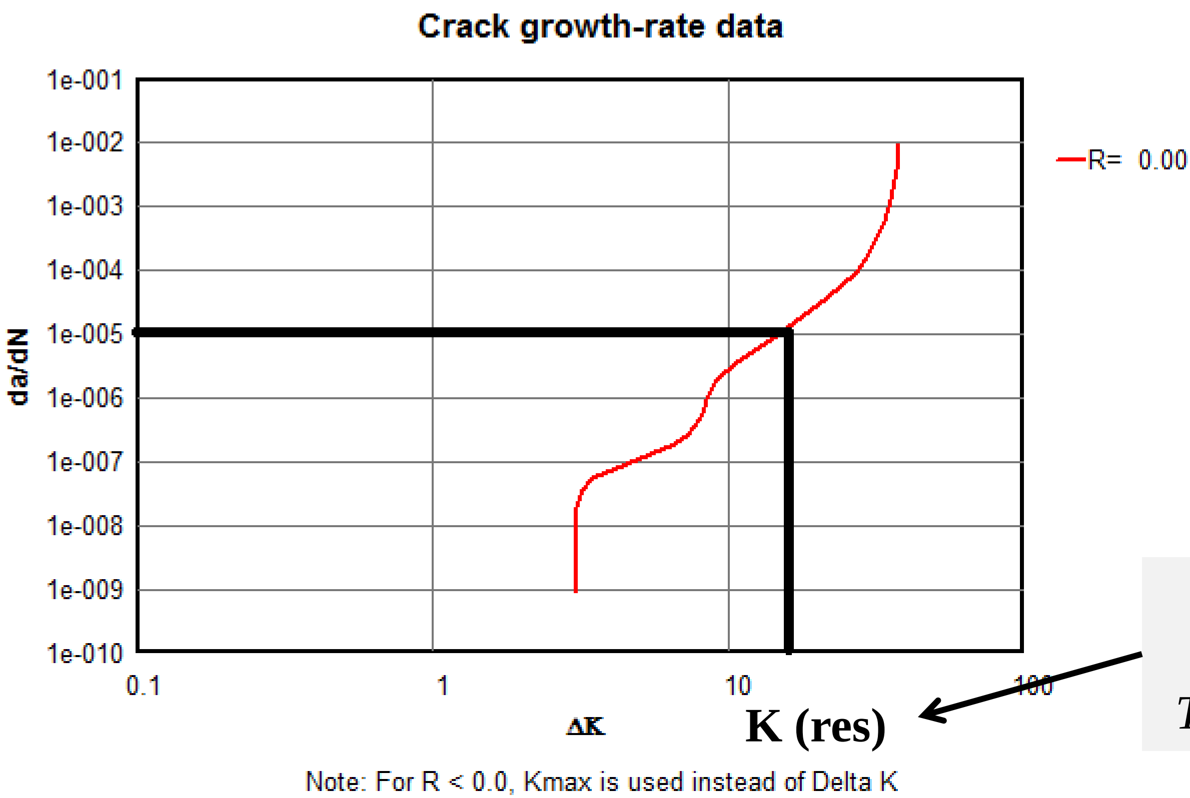
$$K_{res,backward}\ (da/dN_{res}\ ,\ \mathbf{R(LEFM) = 0})$$

$$\sigma_{res}\ (K_{res,backward}\ ,\ \beta_{backward},\ a)$$

$$K_{res,forward}\ (\sigma_{res}\ ,\ \beta_{forward},\ a)$$

Why?
Based on direct measurement

Superimposes Velocities…
i.e…
Conservation of Momentum



da/dN (res)

K (res)

Assumes:
dK = Kres- 0
Thus: Use R = 0

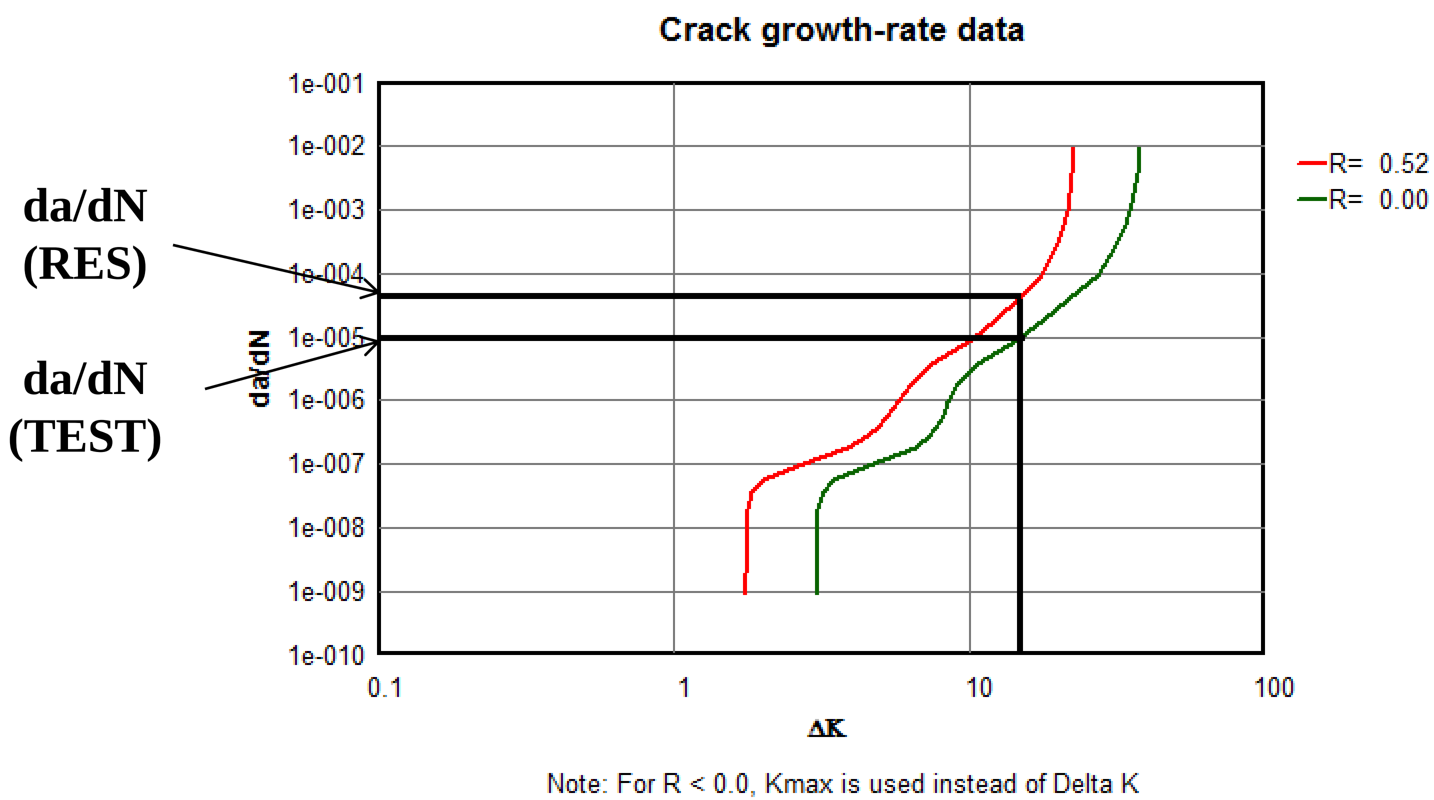
Method #1: K_{res} ‘Classic’ in 2D

$$R_{res}\ (\Delta K,\ da/dN_{test})\ \text{->}\ K_{res,backward}(R_{res})$$

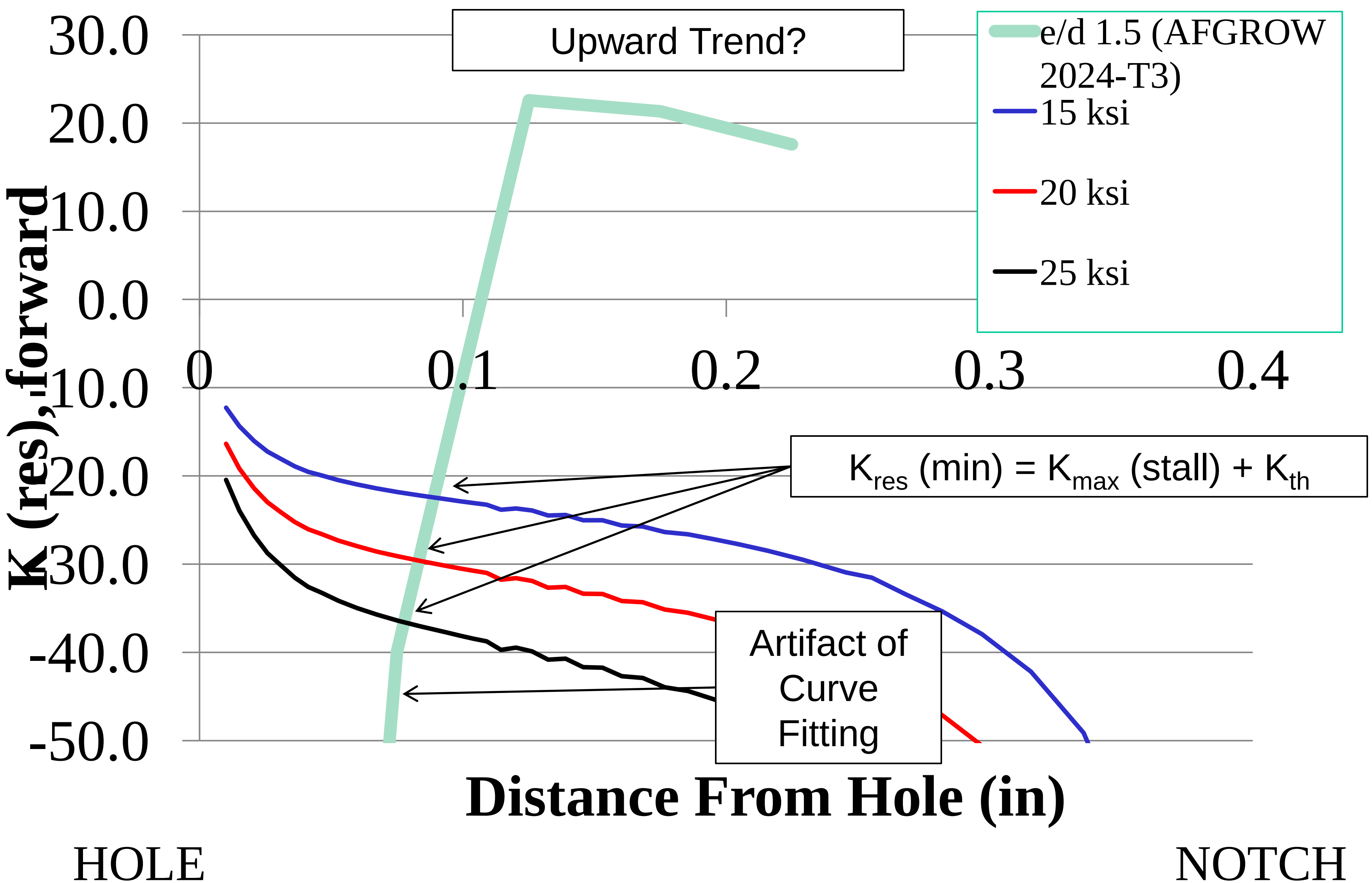
$$\text{Where: } R_{res} = (K_{min} + K_{res}) / (K_{max} + K_{res})$$

$$\sigma_{res}\ (K_{res,backward}\ ,\ \beta_{backward},\ a)$$

$$K_{res,forward}\ (\sigma_{res}\ ,\ \beta_{forward},\ a)$$



Inversion of the Residual Stress Field K(res) for e/d = 1.5



Inversion of the Residual Stress Field K(res) for e/d = 2.0