

# Backwards Calculation of Residual Stress ( $RS_{BC}$ )

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12 Sept 2023

# History Lesson

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Historically we have been inconsistent when predicting crack growth and crack shape in highly compressive residual stress fields

The community has been invested in understanding how to overcome these differences through measurement, testing, process modeling, and analysis

In 2021 HE investigated the effects of unit stresses on SIF extractions, and from that a method was developed to utilize modifications to RS to predict crack growth life

After presenting this work to the A-10 team a test plan was developed in order to better utilize previous test and measurement programs

# Agenda

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- How does RS effect crack growth?**
- Unit RS effects on SIF
- Backwards Calculation of RS process
- Backwards Calculation example
- Current proposed test plan

# How does RS effect crack growth?

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## Known Knowns

- Small changes in RS can have large changes in fatigue predictions
- Small changes in RS can have large changes in crack shape
- We do not predict crack growth shape of Cx holes very well

## Known Unknowns

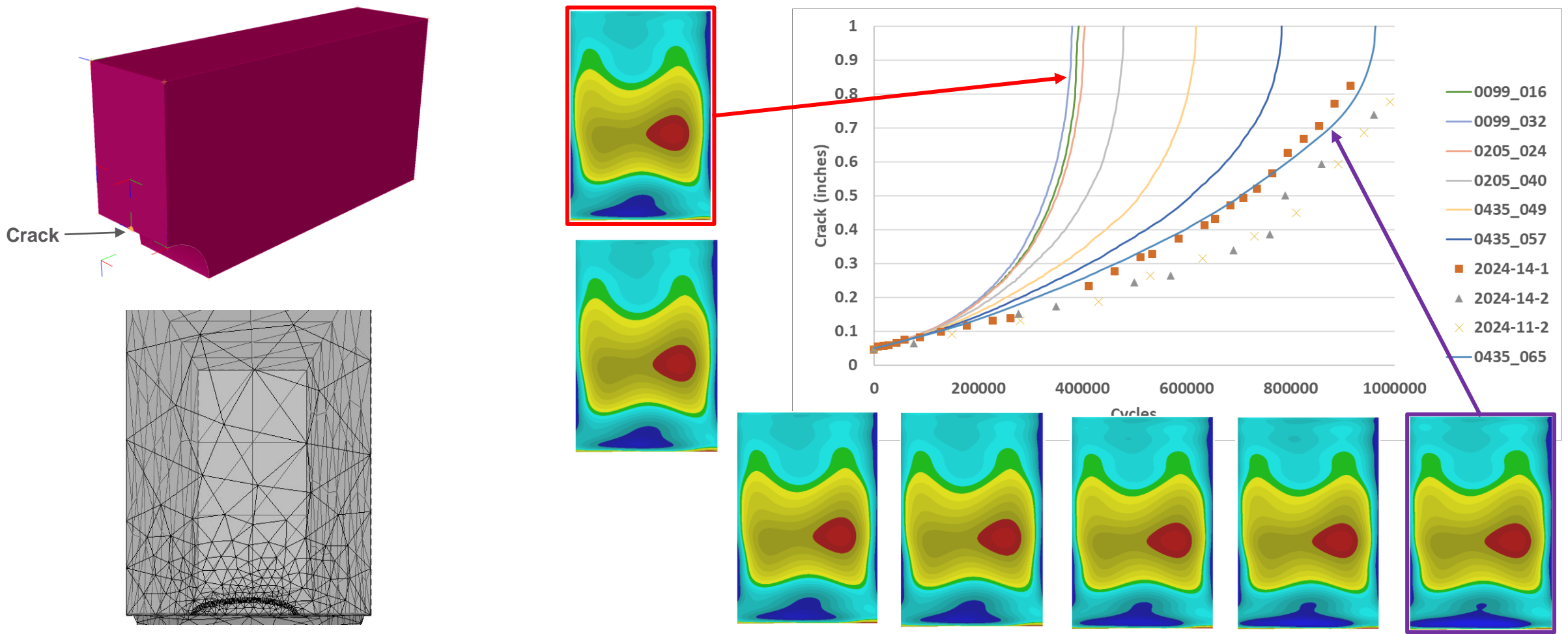
- Why the test data does not match our predictions with the RS fields we currently utilize
- What effects RS have at certain locations on the crack face
- Where should we focus our efforts to gain a comprehensive understanding of the RS field

## What could differences in the measured RS physically represent:

- Process variation
- Measurement error
- Crack closure
- Relaxation
- Other?

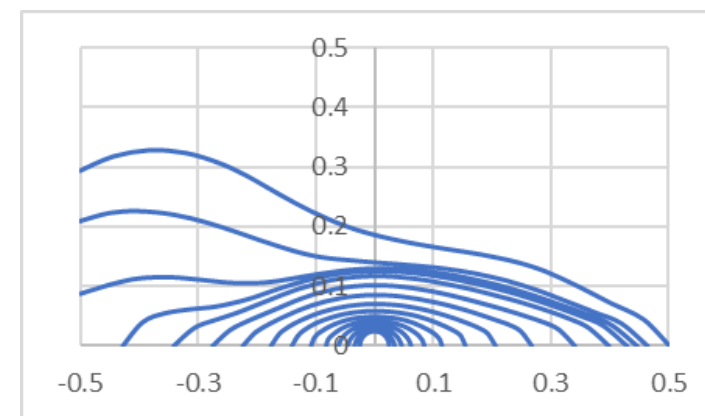
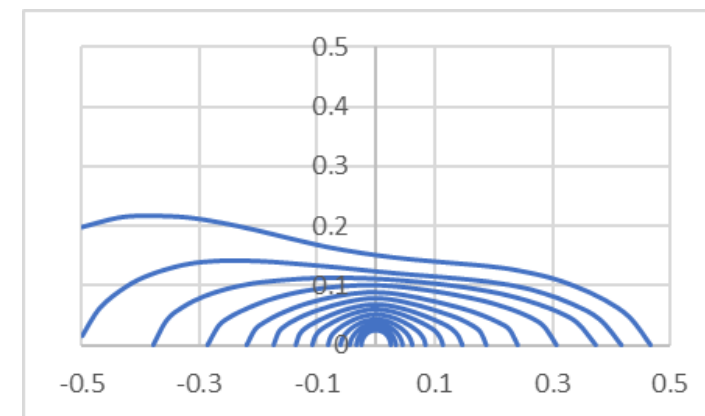
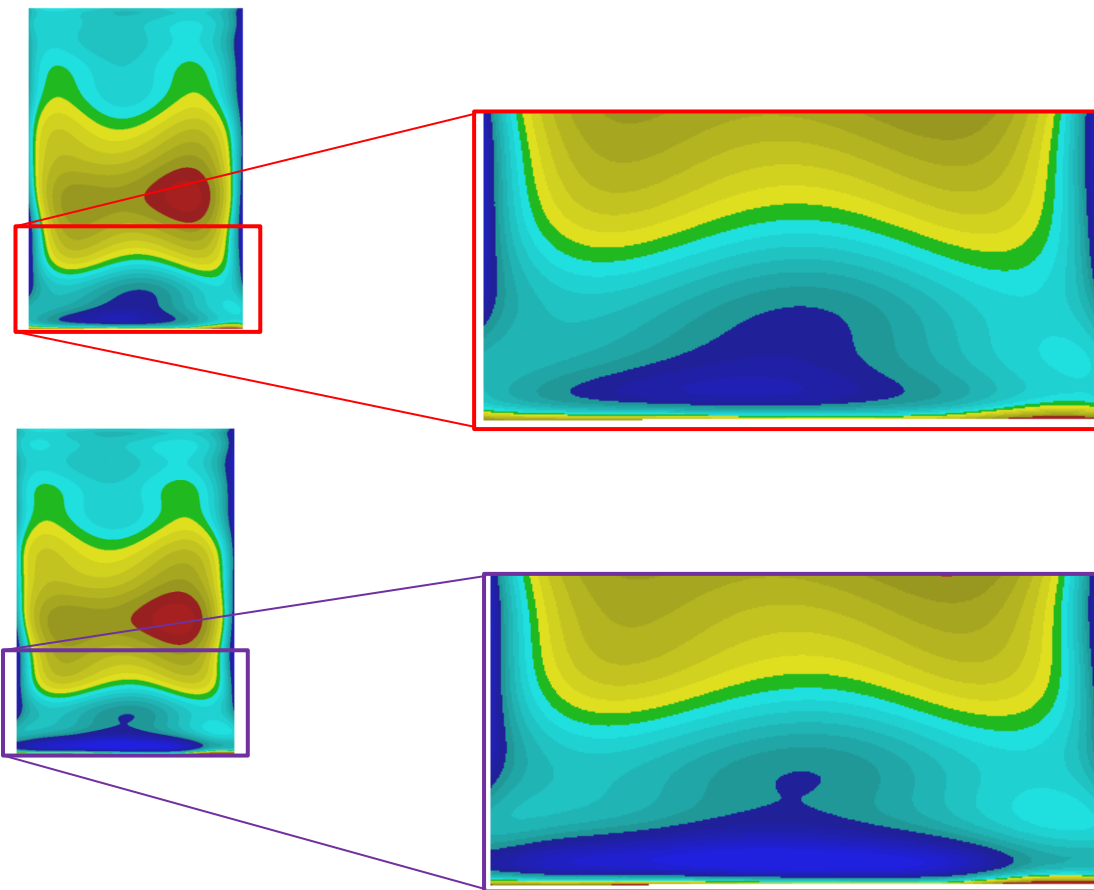
# How does RS effect crack growth?

❑ Small differences between RS fields dramatically effect FCG lives



# How does RS effect crack growth?

- ❑ Small differences in RS fields effect crack shape



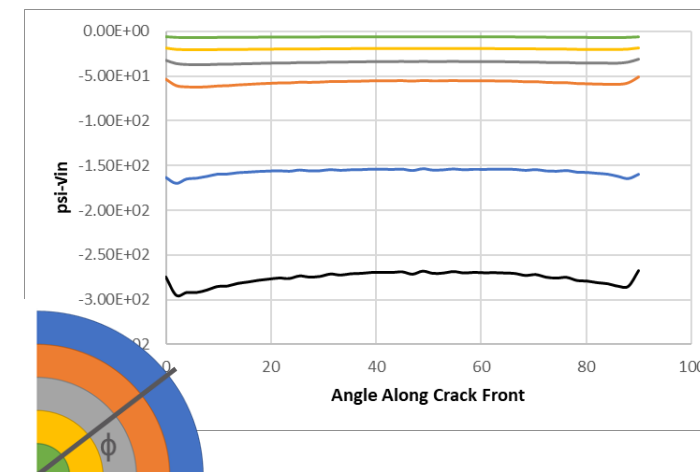
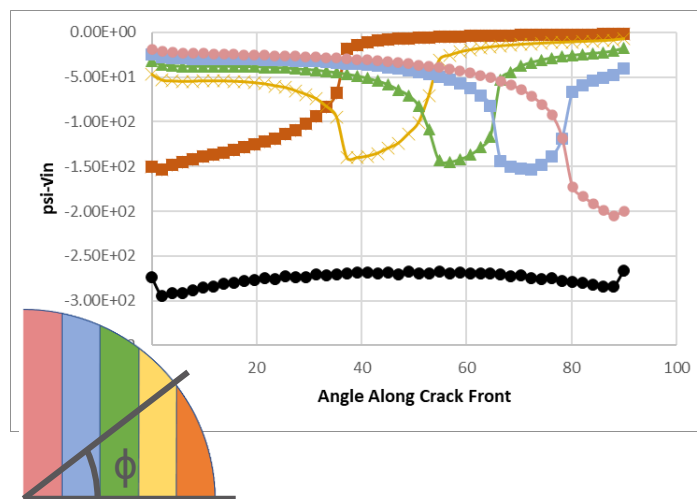
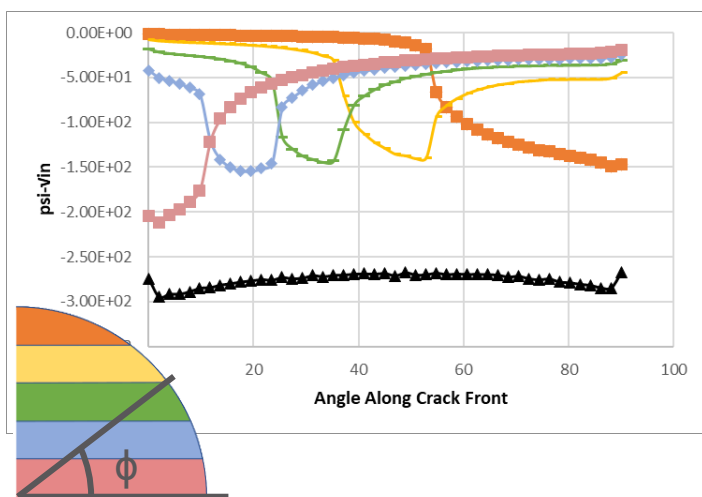
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# Unit RS effects on SIF

- ❑ Applied a unit crack face traction on each color segment
  - ❑ 0.05” quarter circular crack with five 0.01” segments
- ❑ Extracted SIF of crack front
- ❑ Superposition holds for crack face traction
- ❑ SIF is higher at the location the RS is applied

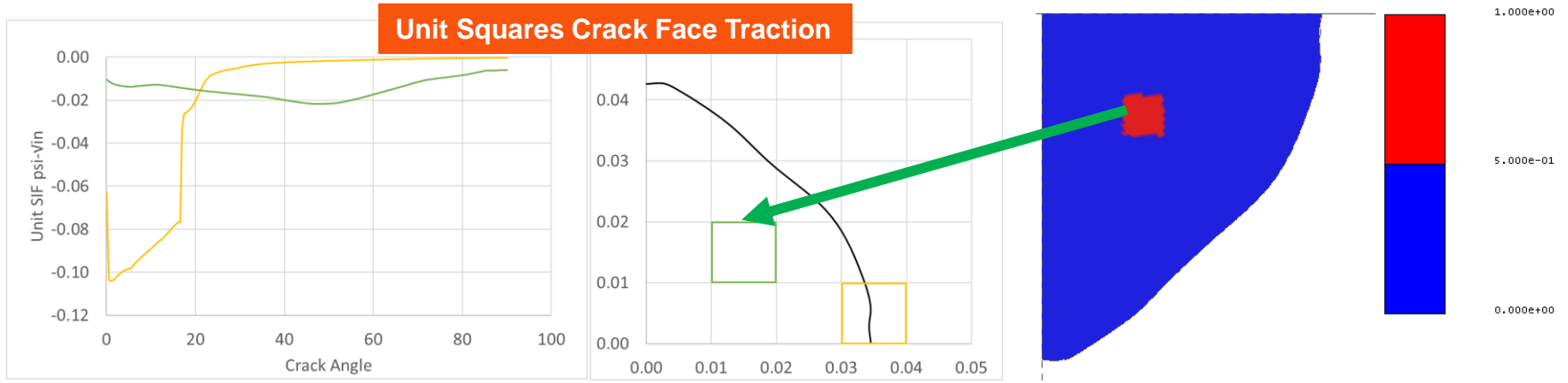




# Unit RS effects on SIF

- Blocks of RS were applied to see the effects of areas not associated with the crack front

$K_{unit\_rs\ x_1y_1}$   
 $K_{unit\_rs\ x_3y_0}$



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# Backwards Calculation of RS Process

## What is the process?

- Directly model marker bands in StressCheck
- Apply blocks of unit stresses to the crack face  $K_{unit\_rs_{x_i y_j}}$
- Calculate  $\Delta K_{eff}$  for each crack size using unit residual stress blocks multiplied by a scalar  $Corr_{x_i y_j} K_{unit\_rs_{x_i y_j}}$
- Modify the scalar  $Corr_{x_i y_j}$  to flatten the  $\Delta K$  curve

$$K_{rsbc} = \sum_i \sum_j Corr_{x_i y_j} K_{unit\_rs_{x_i y_j}}$$

$$K_{min\ total} = K_{min\ app} + K_{rsbc}$$

$$K_{max\ total} = K_{max\ app} + K_{rsbc}$$

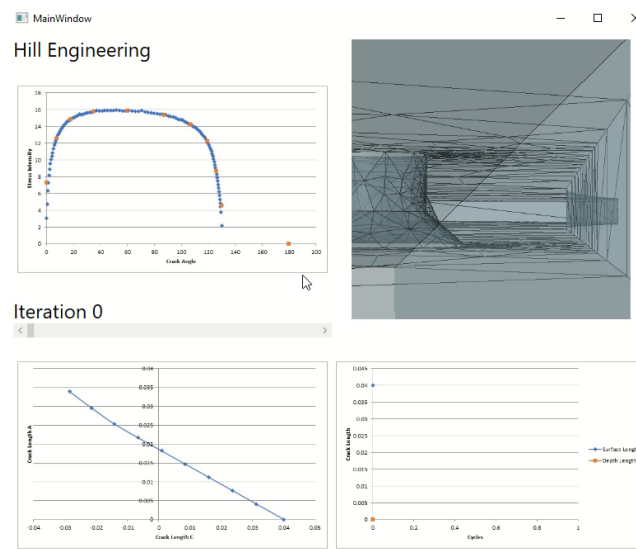
$$\Delta K_{eff} = K_{max\ total} - K_{min\ total}$$

This process assumes all inputs are correct and the discrepancy in the analysis is due to the residual stress

# Backwards Calculation of Residual Stress Process

## What are we doing?

- ❑ Flatlining of  $\Delta K$  is the natural tendency of the crack as it grows through complex stress fields
- ❑ Peaks in the  $\Delta K$  curve relate to higher growth rates
- ❑ Higher growth rates extends the crack faster dampening the  $\Delta K$  curve as the crack progresses
- ❑ This process drives the  $\Delta K$  curve to be flat (equilibrium)
- ❑ Differences in measured RS and bulk RS in the coupon could lead to differences in the observed growth



# Backwards Calculation of Residual Stress Process

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## What is required?

- Good marker bands with corresponding test life
- Accurate baseline data (material data)
  - Matching a baseline test in crack shape and life should be considered
- Reasonable starting point for RS guesses
  - Overall contour shape is good to use as an initial guesses

## What assumptions are made?

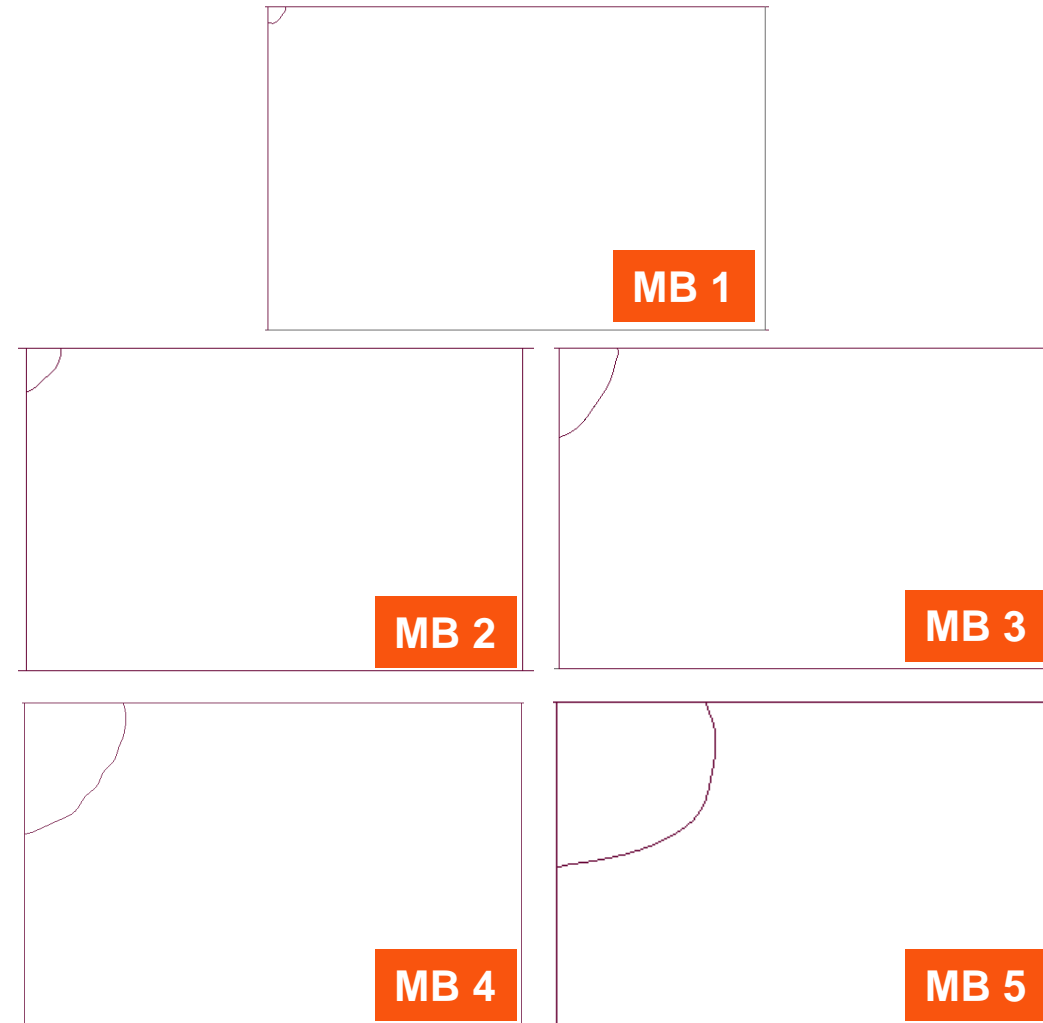
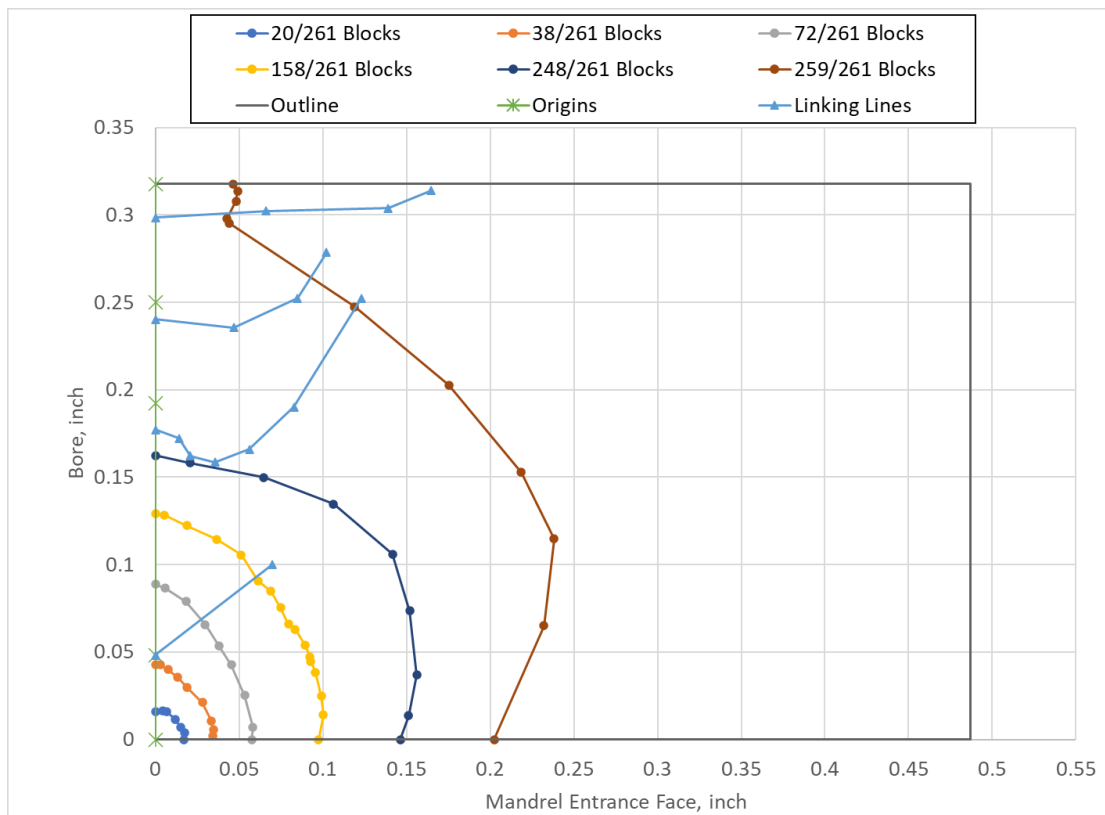
- $\Delta K$  flatlines over the entire crack front
- Each point along the crack front is at the same stress ratio, typically below  $R_{lo}$
- $R < 0$  so  $K_{max}$  is used for all cases
- $da/dN$  vs  $\Delta K$  curve is “correct”

**This process assumes all inputs are correct and the discrepancy in the analysis is due to the residual stress**

# Backwards Calculation of Residual Stress Process

## What is the process?

- ☐ Explicitly model marker bands in StressCheck



# Backwards Calculation of Residual Stress Process

## What is the process?

- Utilize stresscheck model to extract  $K_{applied}$ ,  $K_{rs}$ , and  $K_{unitRS}$  for all unit squares

StressCheck COM - SIF Macro V5.0

Start Solving on Row number	1067	
Solution Options	Check & Solve	
Viewing Options	Show SC	
Save DB files (Yes/No):	Yes	
Auto Mesh	Yes	
Combine Output Files?	No	
Output file Name/Stress (psi)	Combined/MB5_005	10000
Image Capture (If yes include view name)	Yes	Stress

Crack name to calc betas=	xsSTART	p-level	Xstart	Ys
Mod7_ReverseCalc_MB5_Squares.scp	MB5_1	4	0.000	0.0
Mod7_ReverseCalc_MB5_Squares.scp	MB5_2	4	0.005	0.0
Mod7_ReverseCalc_MB5_Squares.scp	MB5_3	4	0.010	0.0
Mod7_ReverseCalc_MB5_Squares.scp	MB5_4	4	0.015	0.0
Mod7_ReverseCalc_MB5_Squares.scp	MB5_5	4	0.020	0.0
Mod7_ReverseCalc_MB5_Squares.scp	MB5_6	4	0.025	0.0
Mod7_ReverseCalc_MB5_Squares.scp	MB5_7	4	0.030	0.0
Mod7_ReverseCalc_MB5_Squares.scp	MB5_8	4	0.035	0.0
Mod7_ReverseCalc_MB5_Squares.scp	MB5_9	4	0.040	0.0
Mod7_ReverseCalc_MB5_Squares.scp	MB5_10	4	0.045	0.0
Mod7_ReverseCalc_MB5_Squares.scp	MB5_11	4	0.050	0.0
Mod7_ReverseCalc_MB5_Squares.scp	MB5_12	4	0.055	0.0
Mod7_ReverseCalc_MB5_Squares.scp	MB5_13	4	0.060	0.0
Mod7_ReverseCalc_MB5_Squares.scp	MB5_14	4	0.065	0.0
Mod7_ReverseCalc_MB5_Squares.scp	MB5_15	4	0.070	0.0
Mod7_ReverseCalc_MB5_Squares.scp	MB5_16	4	0.075	0.0
Mod7_ReverseCalc_MB5_Squares.scp	MB5_17	4	0.080	0.0
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Mod7_ReverseCalc_MB5_Squares.scp	MB5_21	4	0.100	0.0
Mod7_ReverseCalc_MB5_Squares.scp	MB5_22	4	0.105	0.0
Mod7_ReverseCalc_MB5_Squares.scp	MB5_23	4	0.110	0.0

**Formula(e)**

Name	Formula
Szz_Contour	-1000*([-3.1928099030e+01]+-2
Szz_square	IF(x :ge: XStart;IF(x<XStart+0

Name: Szz\_square    Angle Option: 0 to 2pi    System Option: Cartesian

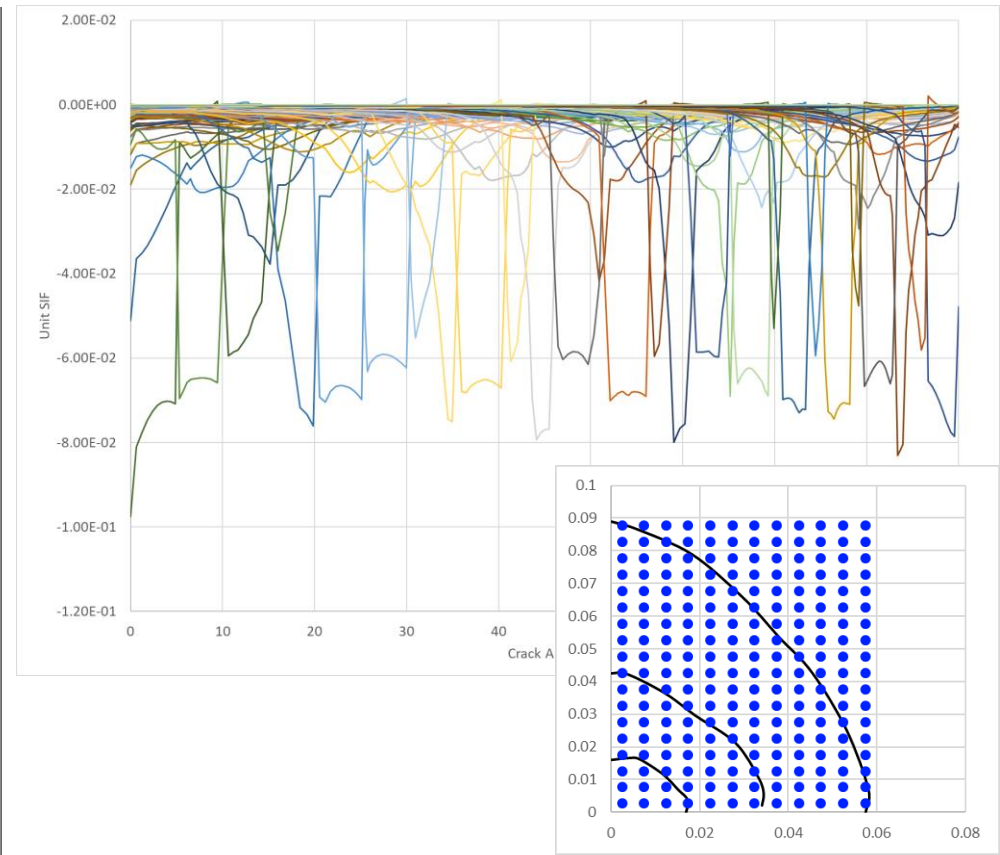
Use Constants: C1: 0.0

Use Subexpressions: (1)

Formula: {X,Y,Z}

IF(x :ge: XStart;IF(x<XStart+0.005;IF(y :ge: YStart;IF(y<YStart+0.005;1;0);0);0)

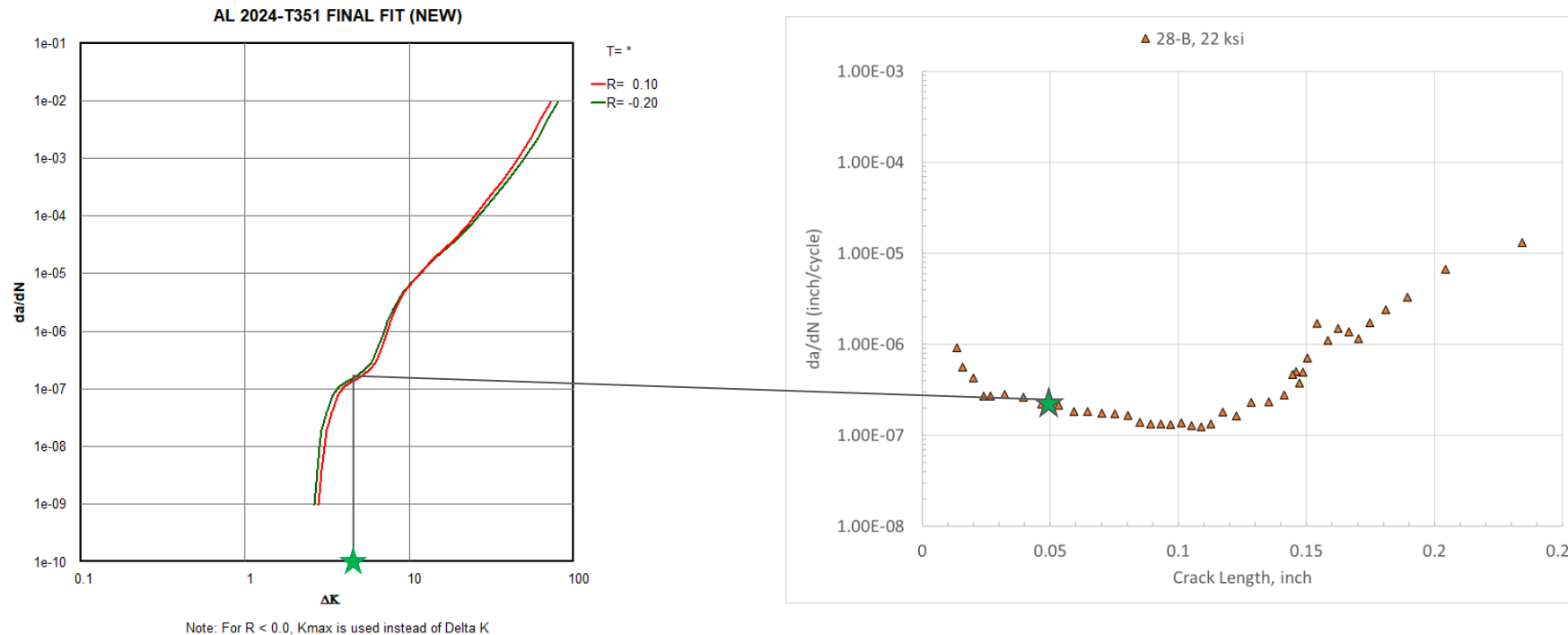
Simulation | Parameters | Rules | **Formula(e)**



# Backwards Calculation of Residual Stress Process

## What is the process?

- Utilize growth rates from test data to determine  $\Delta K_{total}$ , this provides the goal for utilization of the flatline process
- Use  $K_{max}$  at  $R_{lo}$  for most CX applications

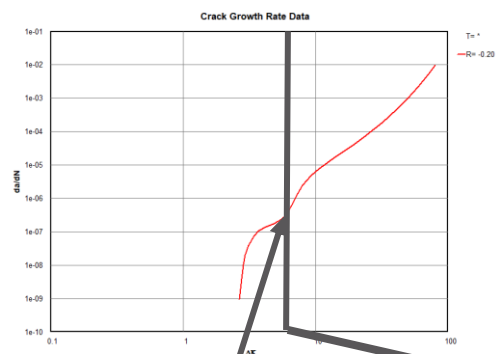




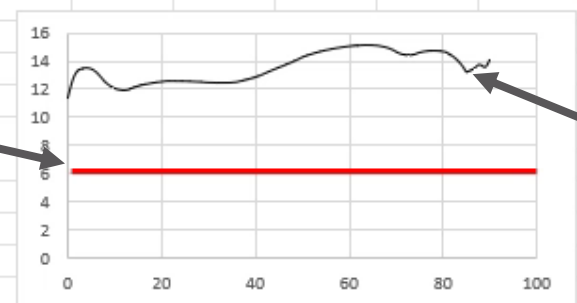
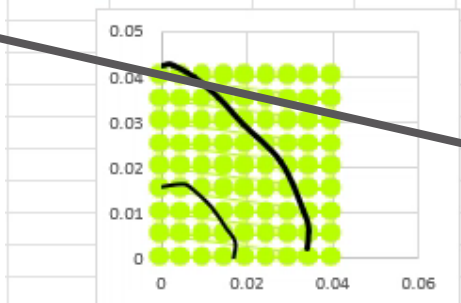
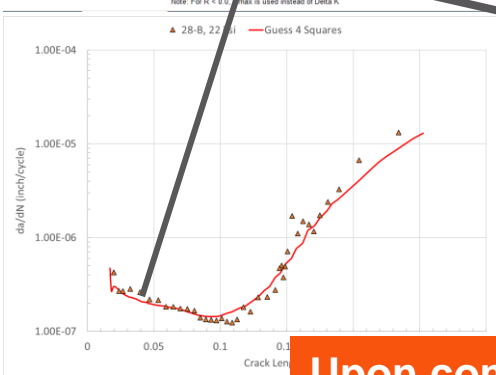
# Backwards Calculation of Residual Stress Process

## What is the process?

- Build complex excel sheet that references each SIF extraction
- Modify  $\Delta K_{eff}$  for each crack size using each unit residual stress multiplied by a correction
- Iterate through the scalars to “flatten” the  $\Delta K_{eff}$  curve using the test surface rates



	0.000001	0.005	0.01	0.015	0.02	0.025	0.03	0.035	0.04
0.000001	-4.455867057	-8.69395	-15.6203	-22.3127					
0.005	-14.8643075	-15.3706	-19.5982	-24.3916					
0.01	-24.07639377	-21.3734	-23.2873						
0.015	-32.08761536	-26.6337							
0.02									
0.025									
0.03									
0.035									
0.04									



$$K_{rsbc} = \sum_i \sum_j Corr_{x_i y_j} K_{unit\_rs_{x_i y_j}}$$

$$K_{min} = K_{min\_app} + K_{rsbc}$$

$$K_{max} = K_{max\_app} + K_{rsbc}$$

$$\Delta K_{total} = K_{max} - K_{min}$$

Upon completion of all marker bands perform a BAMpF Analysis

# Agenda

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- Unit RS effects on SIF
- Backwards Calculation of RS process
- Backwards Calculation Example**
- Current proposed test plan**

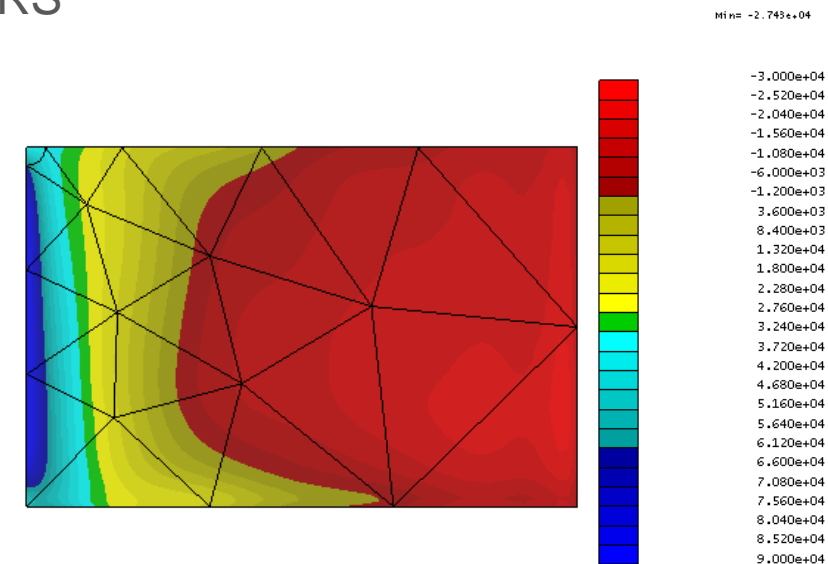
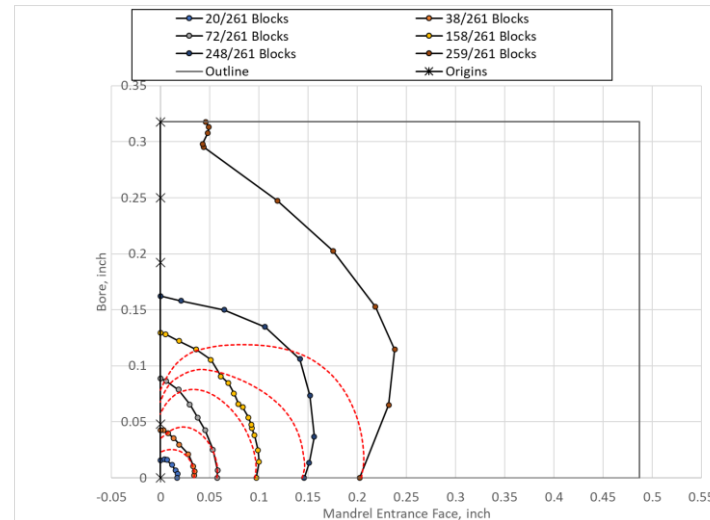
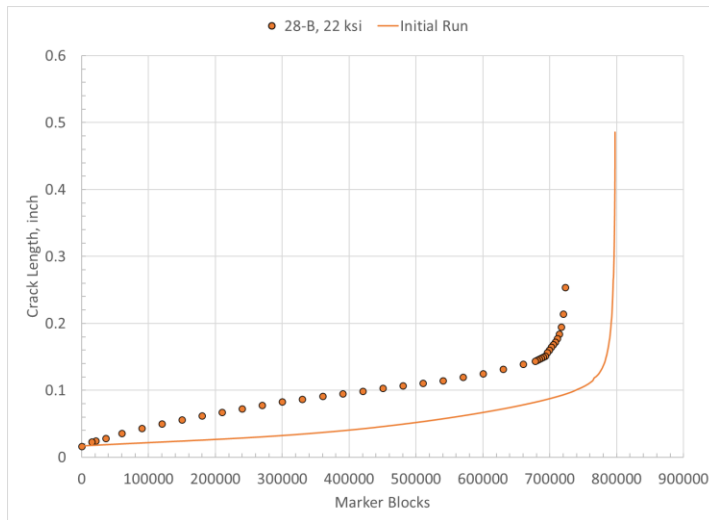
# Backwards Calculation Example

## Received data from AP/ES

- 3d1-28-B
  - W-1.5"; t-0.313";  $\sigma_{max}$  -22 ksi R=0.1
  - 6 total marker bands

## Initial analysis used contour result 3K1-02-B from RS Database

- Reasonable life prediction
- Analysis shows significant pinning at the bore indicative of too much RS



# Backwards Calculation Example


## Utilizing 0.005" Unit RS Squares

- Utilized StressCheck Excel COM to extract and combine SIF curves
- Assume the SIF from the surface using strips are “correct”
- “Flat Line”  $\Delta K_{total}$  curve for each marker band by scaling squares
- Squares should maintain their value from previous MB corrections

IF(x :ge: XStart;IF(x<XStart+0.005;IF(y :ge: YStart;IF(y<YStart+0.005;1;0);0);0);0)

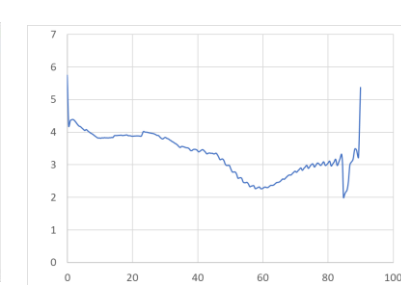
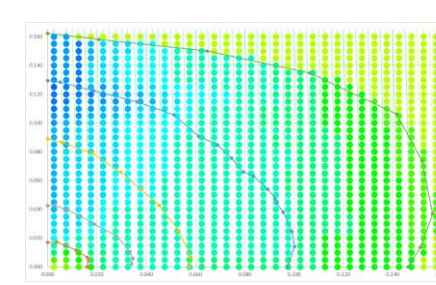
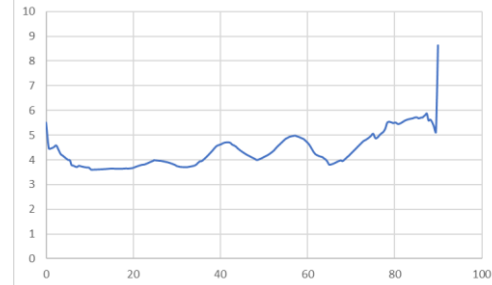
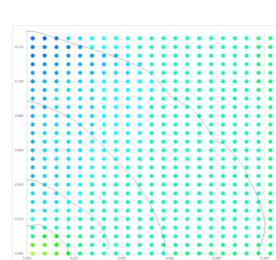
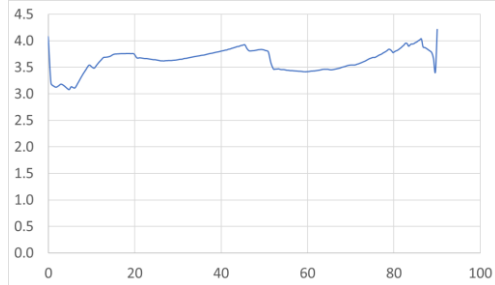
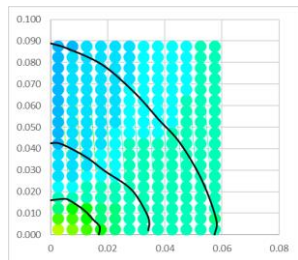
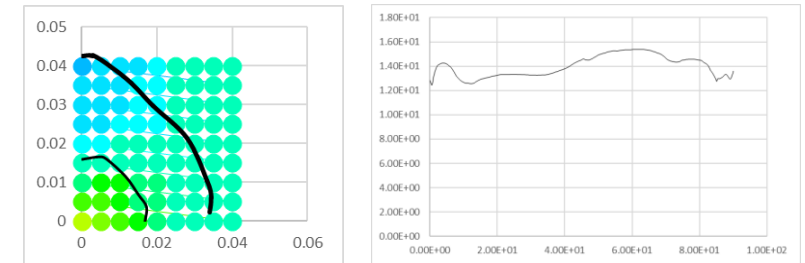
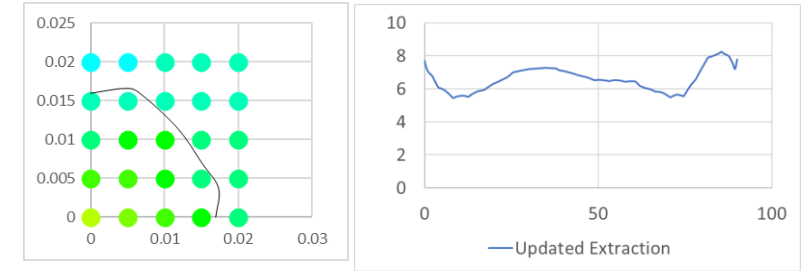
**StressCheck COM - SIF Macro V5.2**

Start Solving on Row number	1067	
Solution Options	Check & Solve	
Viewing Options	Show SC	
Save SIF files (Yes/No):	Yes	
Auto Mesh	Yes	
Combine Output Files?	No	
Output file Name (Stress/psf)	CombinedMB_005	10000
Image Capture (if yes include view name)	Yes	Stress


[User's Guide  
Double Click to view PDF](#)

Crack name to calc betas=		xSTART	Parameters	Solution ID	Extract
Input File Name	Output File Name	n-level	Xstart	Ystart	
Mod7_ReverseCalc_MBS_Squares.scp	MBS_1	4	0.000	0.000	1-linear Ksol
Mod7_ReverseCalc_MBS_Squares.scp	MBS_2	4	0.005	0.000	1-linear Ksol
Mod7_ReverseCalc_MBS_Squares.scp	MBS_3	4	0.010	0.000	1-linear Ksol
Mod7_ReverseCalc_MBS_Squares.scp	MBS_4	4	0.015	0.000	1-linear Ksol
Mod7_ReverseCalc_MBS_Squares.scp	MBS_5	4	0.020	0.000	1-linear Ksol
Mod7_ReverseCalc_MBS_Squares.scp	MBS_6	4	0.025	0.000	1-linear Ksol

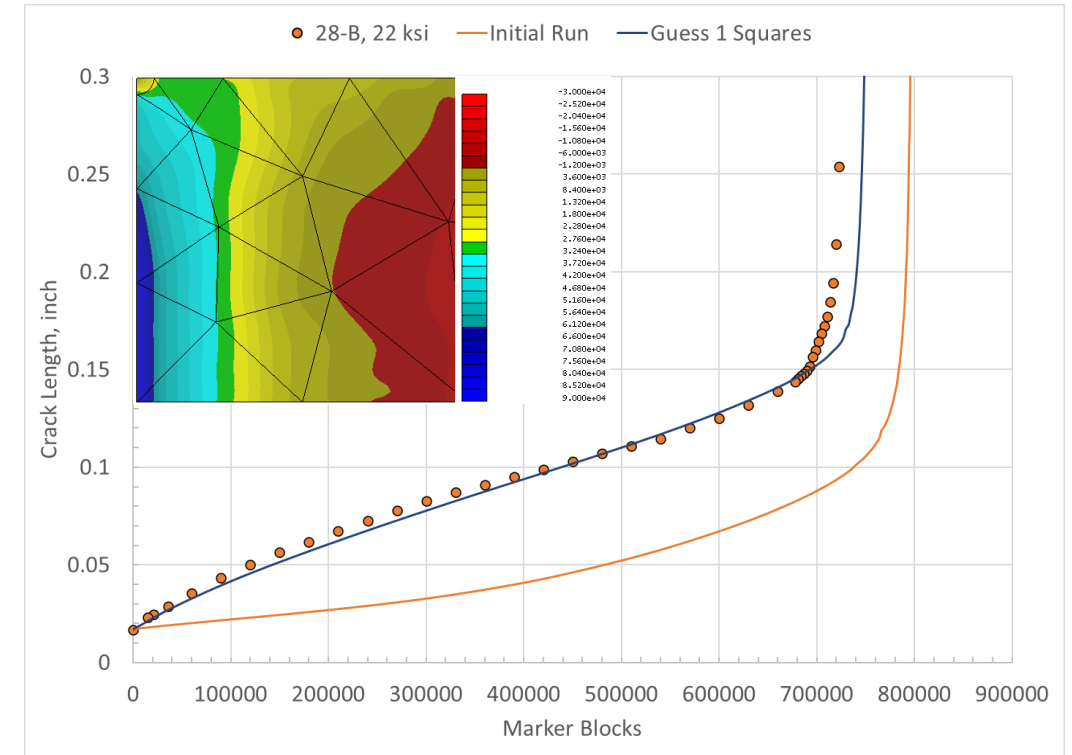
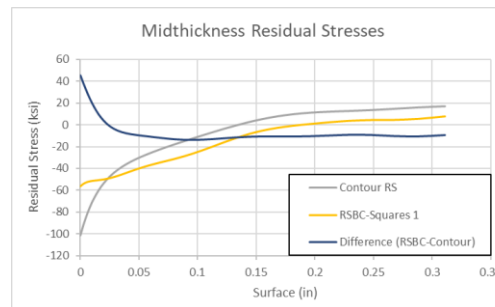
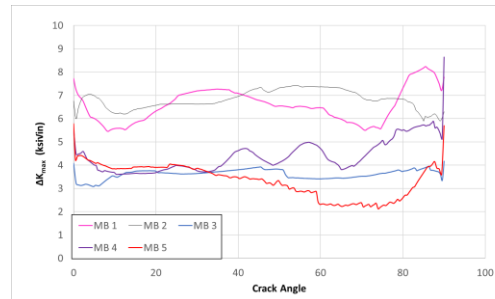
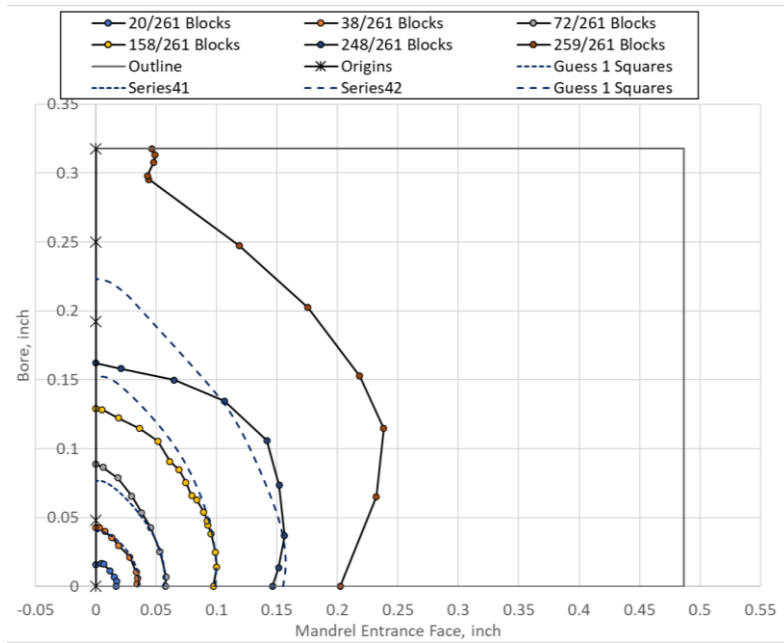
**MB-1 25 solutions**  
**MB-2 81 solutions**  
**MB-3 216 solutions**  
**MB-4 525 solutions**  
**MB-5 1056 solutions**



# Backwards Calculation Example

## Utilization of unit squares with crack face traction

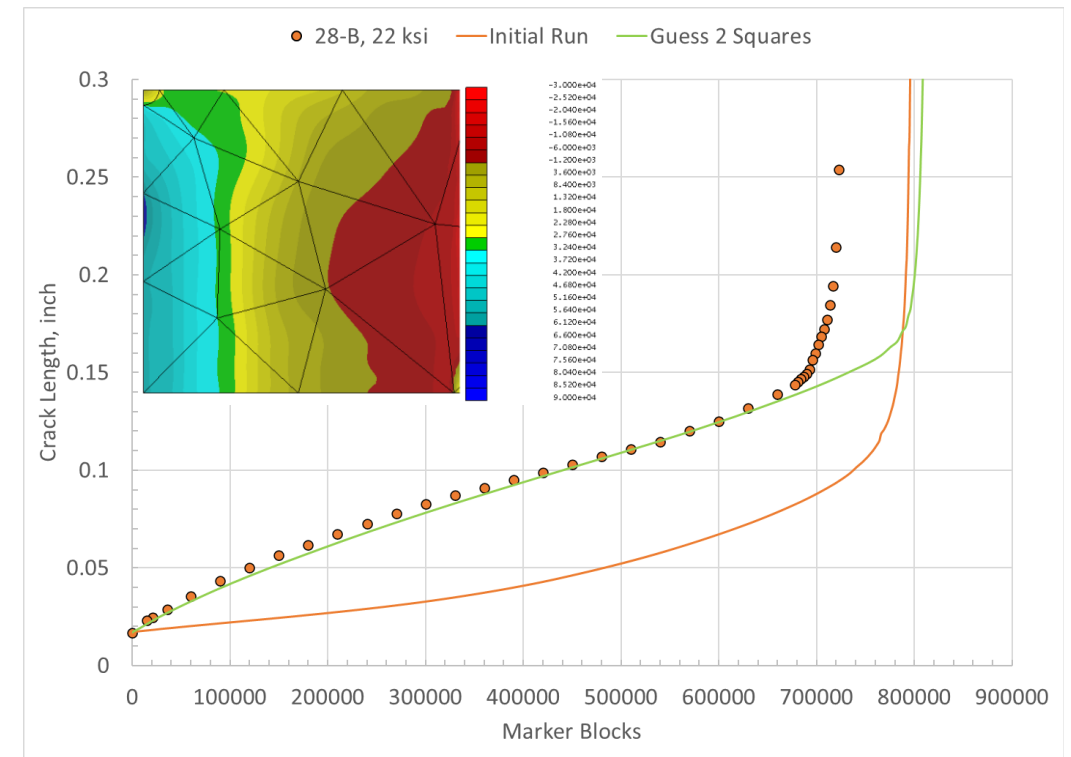
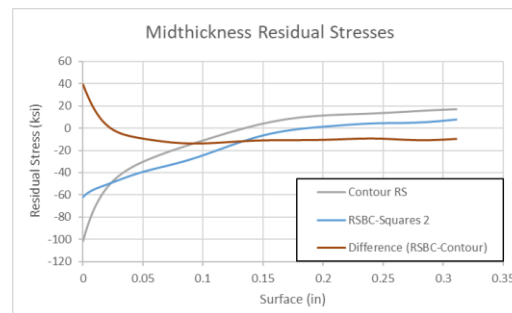
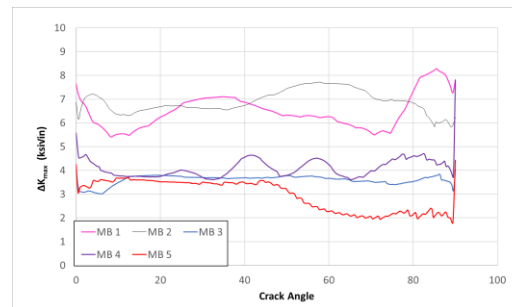
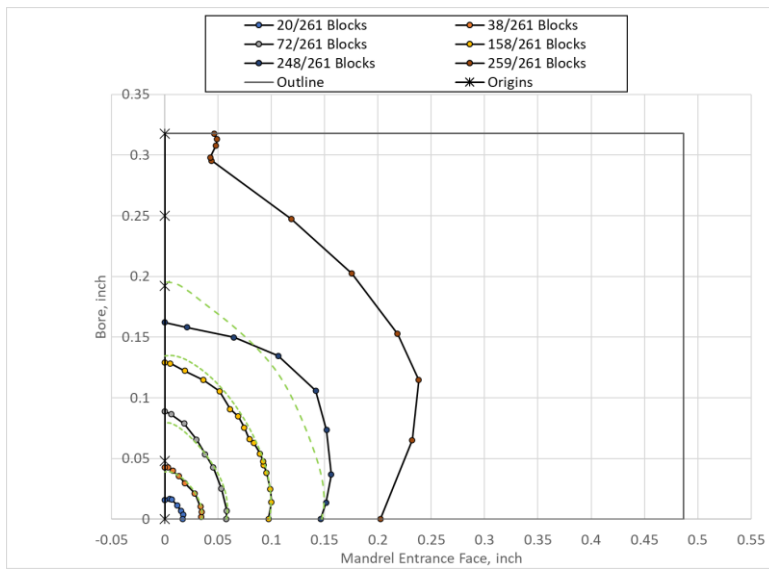
- Initial guess produces similar results to strips
- Better fit for MB3 and 4
- RS at bore surface needs to be increased
- Turn up point is a little high 0.165" vs 0.145"



# Backwards Calculation Example

## Utilization of unit squares with crack face traction

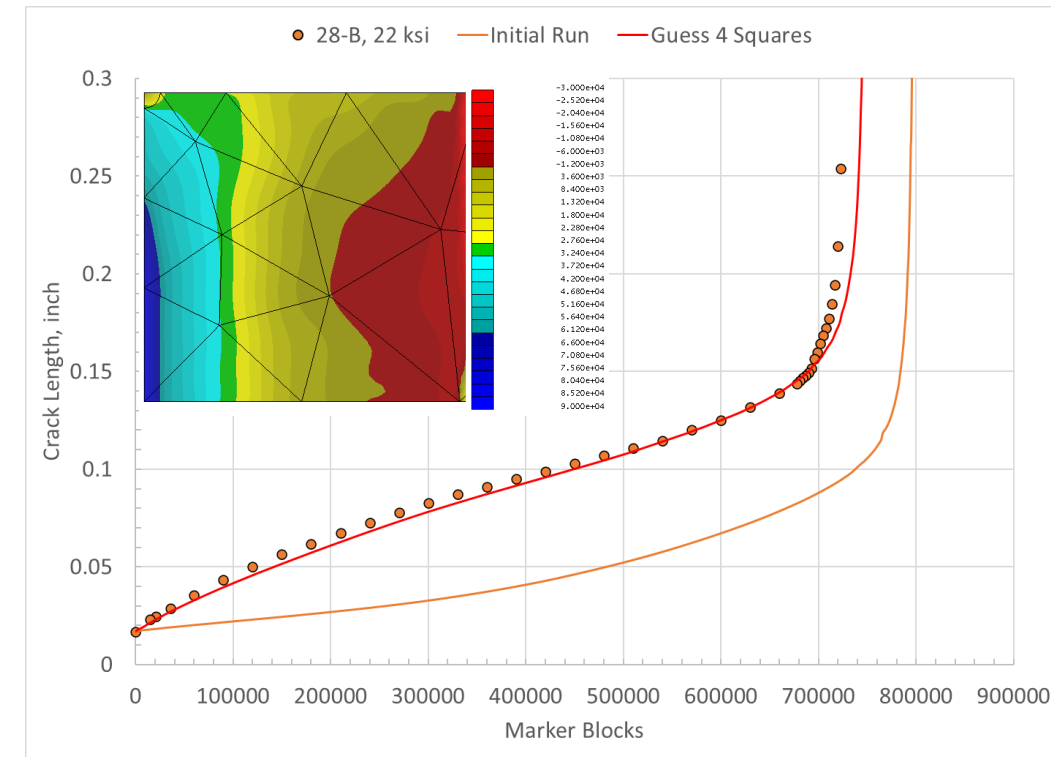
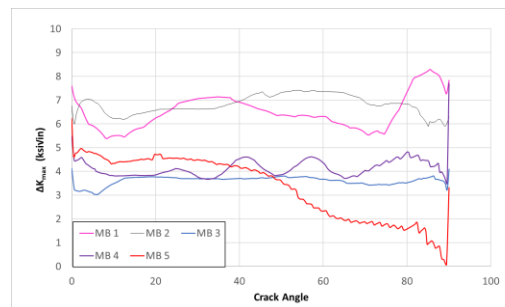
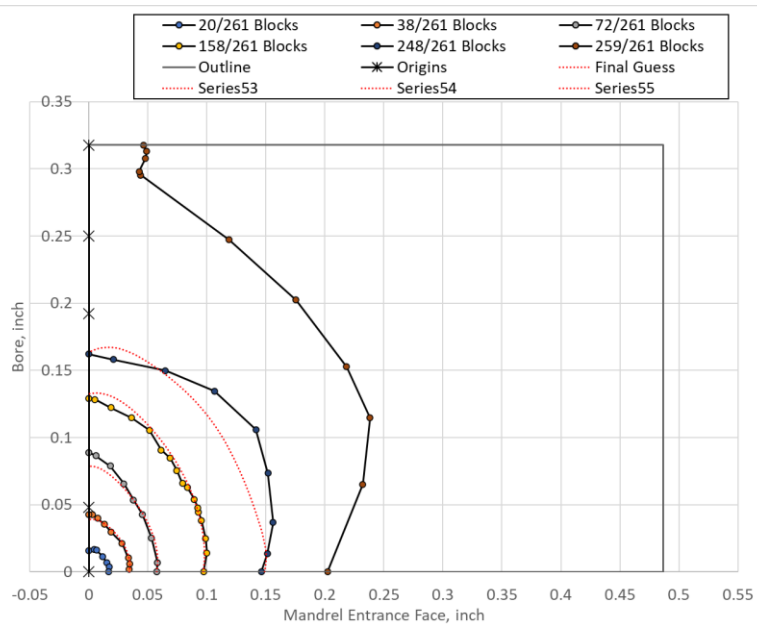
- Small modifications up the bore to work through pinning issues were not enough
- Changes increased the turn up point
- Need to reduce the RS at the surface and increase the RS at the bore between the 3<sup>rd</sup> and 4<sup>th</sup> markers
- Up to 3<sup>rd</sup> marker is good!



# Near Surface Residual Stress: Backwards Calculation

## Utilization of unit squares with crack face traction

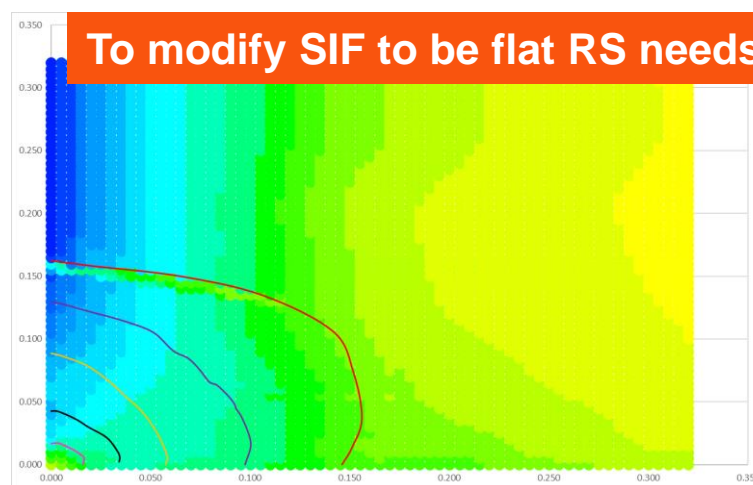
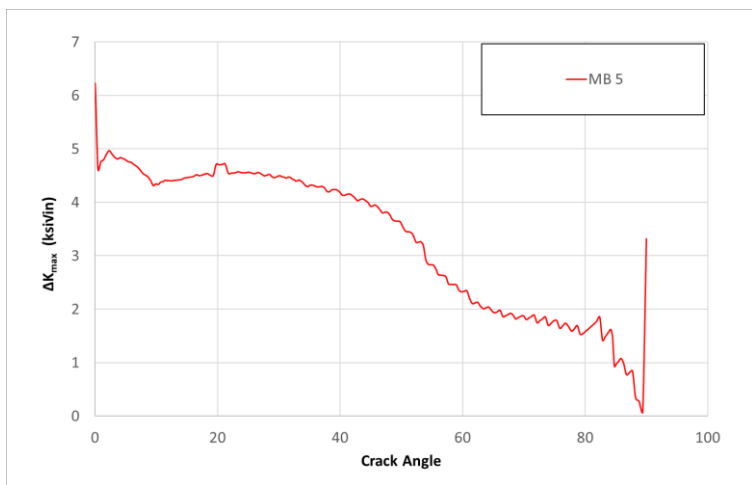
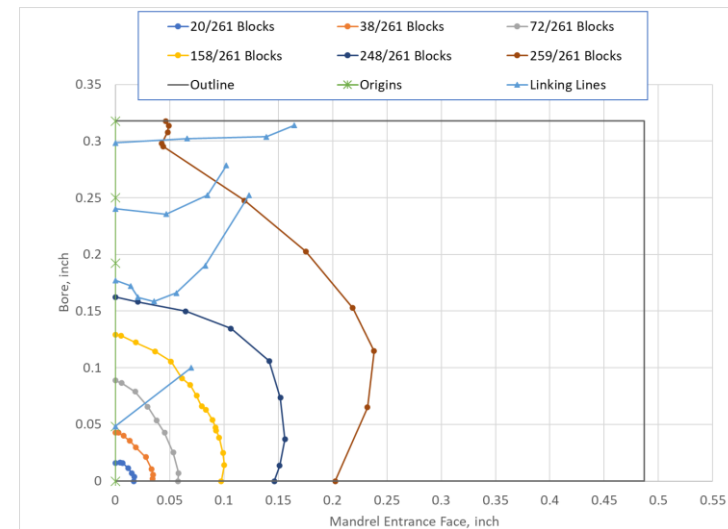
- Small modifications <4 ksi at surface
- Match surface growth well
- Match Markers well to 4<sup>th</sup> Marker Band (95% of life)
- 5<sup>th</sup> Marker band will not flatline



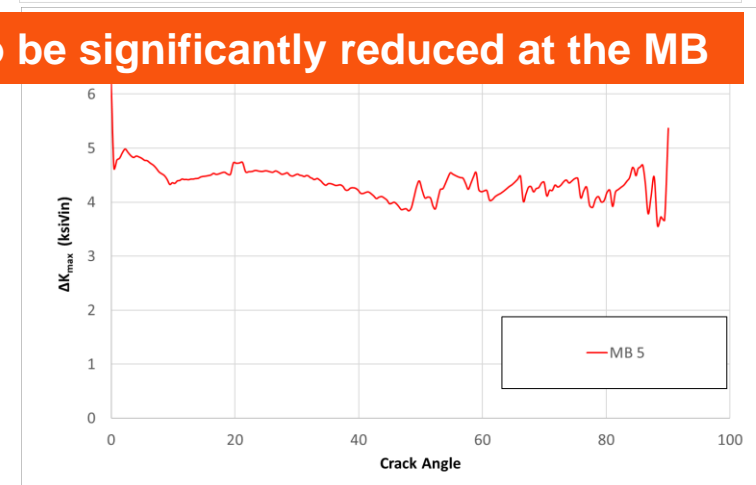
# Backwards Calculation Example

## Secondary Crack Interaction

- With current RS MB's match good up to 4<sup>th</sup> Marker band
- 5<sup>th</sup> SIF curve cannot be driven flat without significantly reducing the RS
- MB maps show 3 nucleation sites above with crack linking lines
- Last marker band shows crack coalescences modifying the crack shape
- Is the secondary cracking shadowing the primary crack?



**To modify SIF to be flat RS needs to be significantly reduced at the MB**





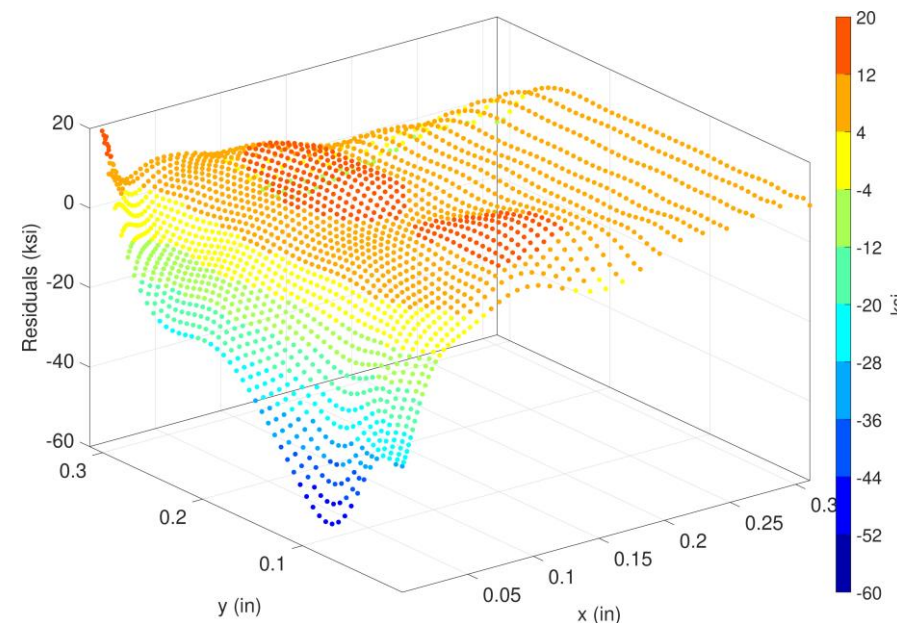
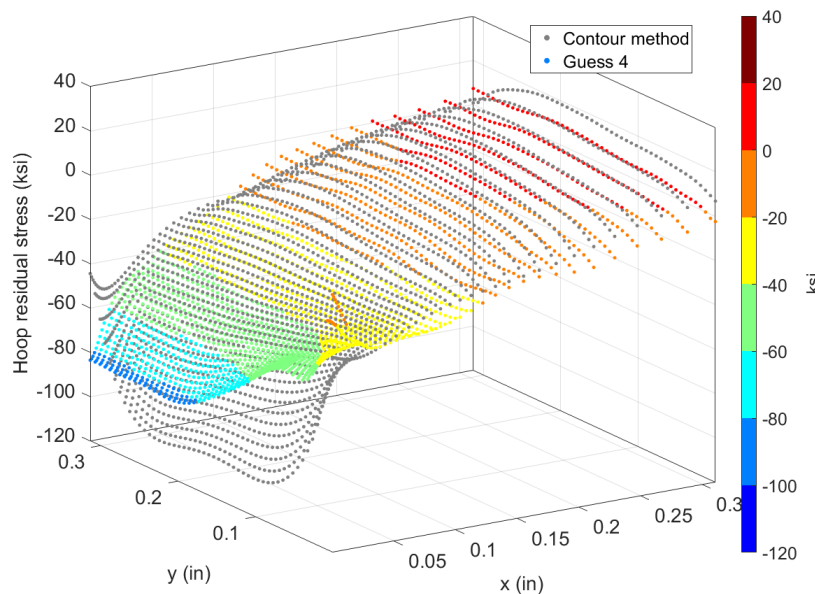
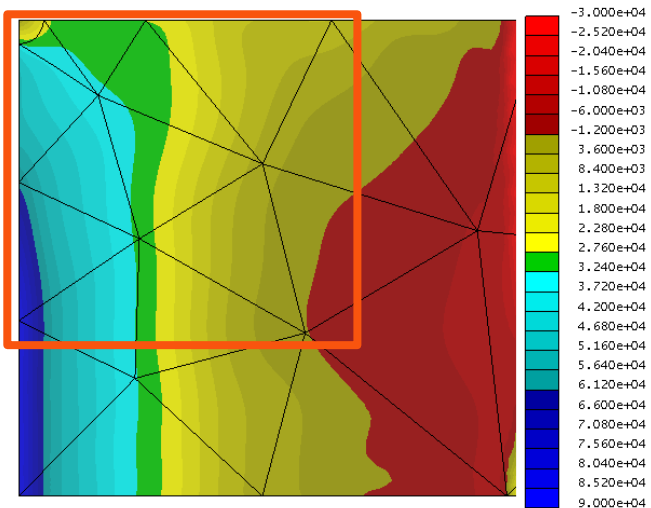
# Backwards Calculation Example

## Conclusions

- A residual stress can be backwards calculated utilizing unit crack face traction squares
- Small differences observed in crack shape to test at larger cracks
- Residual stress field is only valid up to the last marker band observed in test
- Differences in residual stress are significant (~50 ksi peak at bore)



Area of confidence



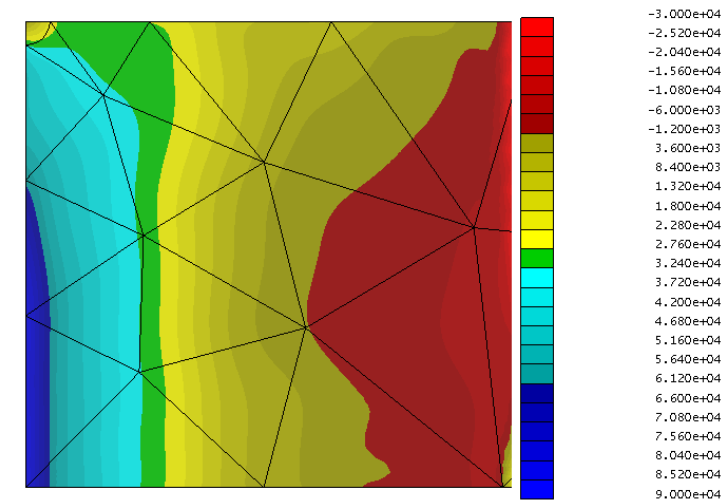
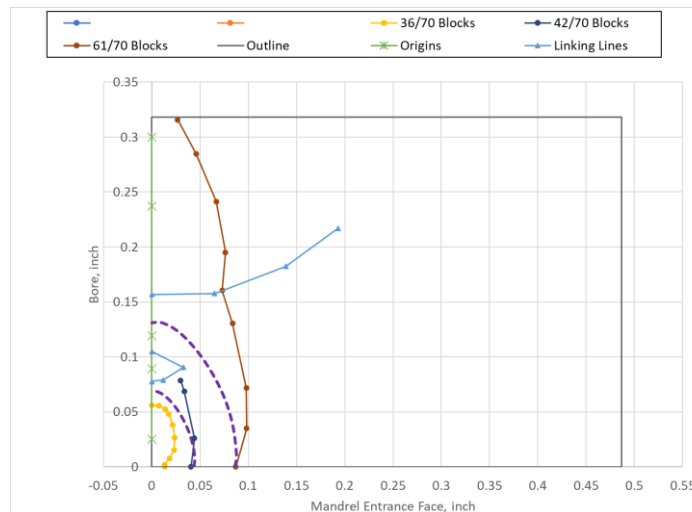
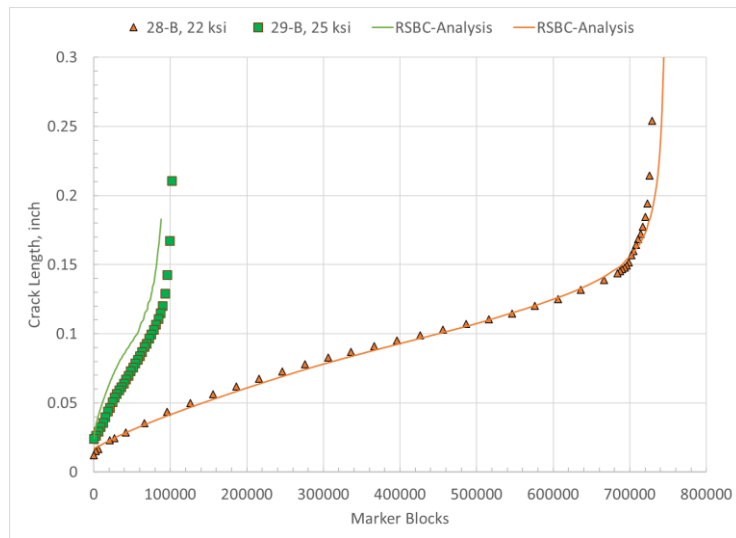
# Backwards Calculation Example

Received data from AP/ES same geometry higher applied stress

- 3d1-29-B
  - W-1.5"; t-0.313";  $\sigma_{max}$  -25 ksi R=0.1
  - 6 total marker bands

Blind prediction used backwards calculation residuals stress from previous test

- Reasonable life prediction
- Analysis shows “good” shape prediction with significant secondary cracking observed in test



# Agenda

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- How does RS effect crack growth?
- Unit RS effects on SIF
- Backwards Calculation of RS process
- Backwards Calculation Example
- Current proposed test plan**

# Current Proposed Test Plan

Two Opportunities to look into this:

Type	CP	Material	Cx Condition	Loading	Qty	Notes
Baseline1	CP XX	2024-T351	NCX	CA + MB	3	Provides confidence in baseline material properties Allows for utilization of surface corrections to match crack shapes
Baseline2			NCX	Spectrum + MB	3	Determine if the surface correction changes based on loading
Baseline1	CP YY	7075-T651	NCX	CA + MB	3	Provides confidence in baseline material properties Allows for utilization of surface corrections to match crack shapes
Baseline2			NCX	Spectrum + MB	3	Determine if the surface correction changes based on loading
Cx1	CP XX	2024-T351	CX	CA + MB	3	Utilize surface correction from baseline post-dictions Perform initial prediction with contour RS (RS database) Perform backwards calculation on test coupon to develop a RS field that matches test data
Cx2			CX	Spectrum + MB	5	Utilize surface correction from baseline post-dictions Utilize backwards calculated RS Perform retardation study to match test data
Cx1	CP YY	7075-T651	CX	CA + MB	3	Utilize surface correction from baseline post-dictions Perform initial prediction with contour RS (RS database) Perform backwards calculation on test coupon to develop a RS field that matches test data
Cx2			CX	Spectrum + MB	5	Utilize surface correction from baseline post-dictions Utilize backwards calculated RS Perform retardation study to match test data
<b>TOTAL =</b>					<b>28</b>	

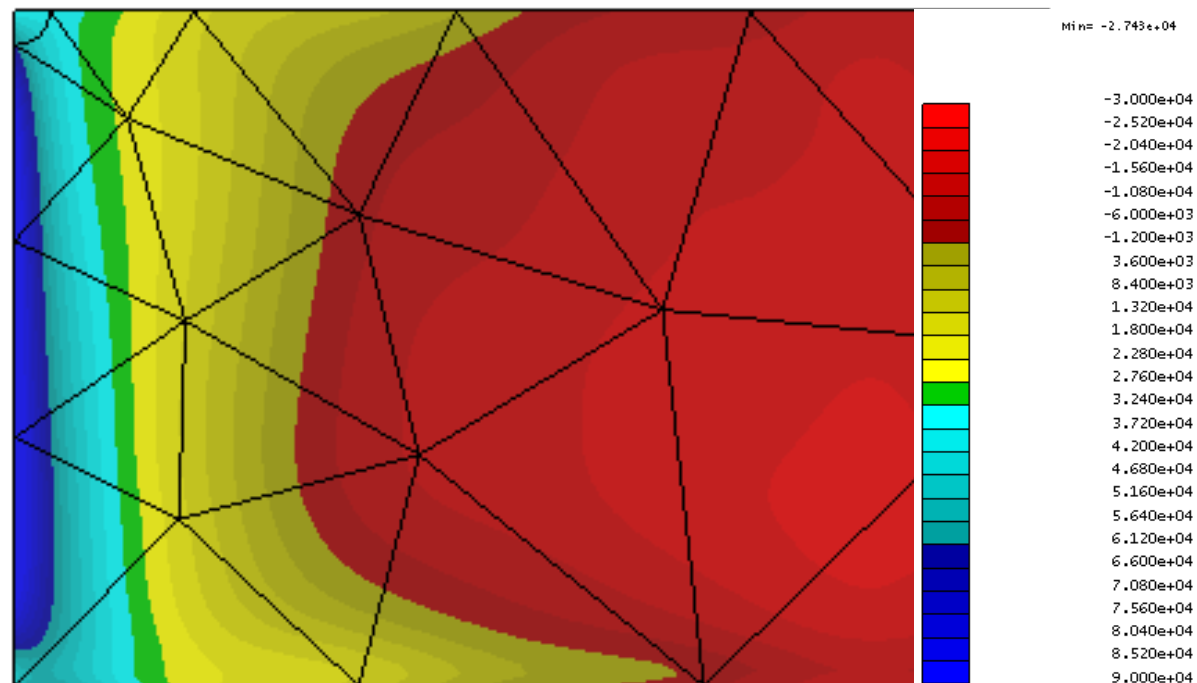
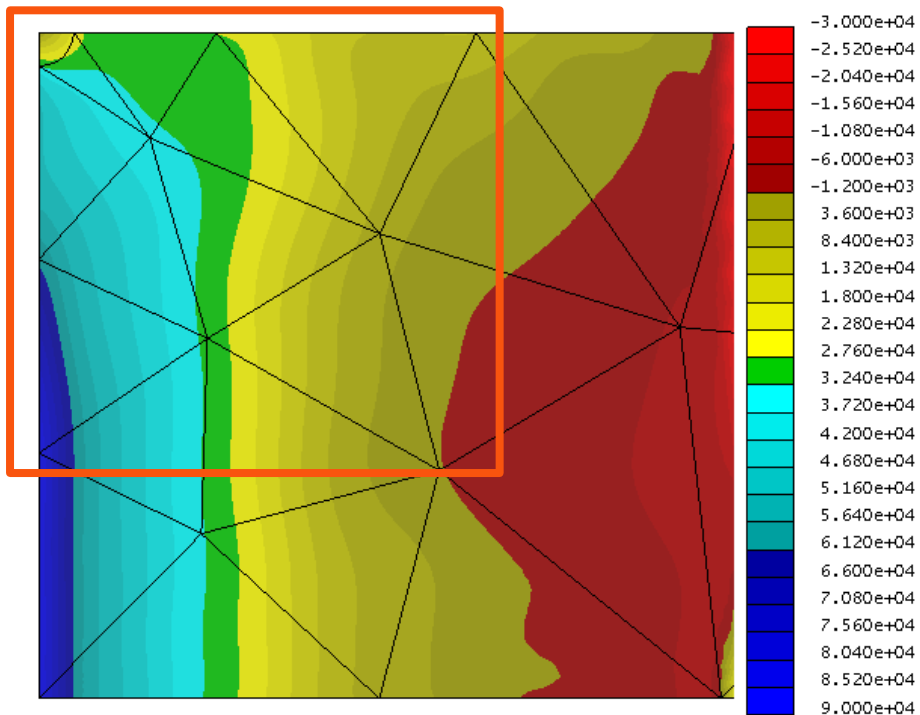
# Current Proposed Test Plan

Repeating tests from AP/ES to get marker bands of crack growth  
 Stress Ratio testing will help us understand the interaction between BCrs and closure.

Material	W (inch)	t (inch)	e (in)	D (inch)	Loading	Max Stress (ksi)	Type	Qty
7075-T7351	2.4	0.25	1	0.4745	R=0.02, 0.1, 0.4, 0.6, 0.7, 0.8	27.0	Cx	6

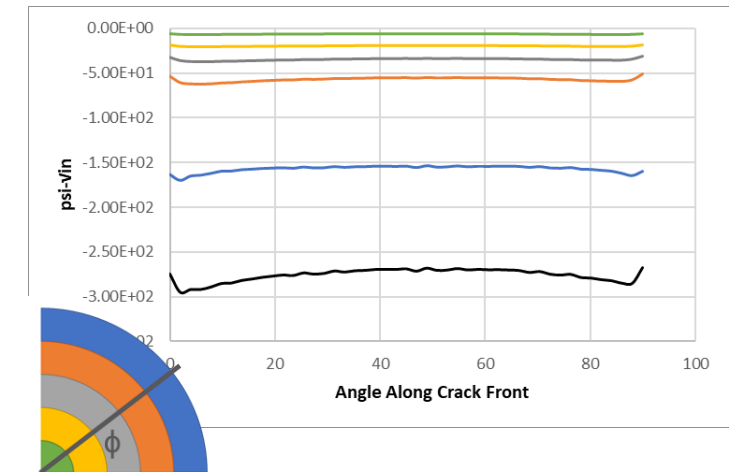
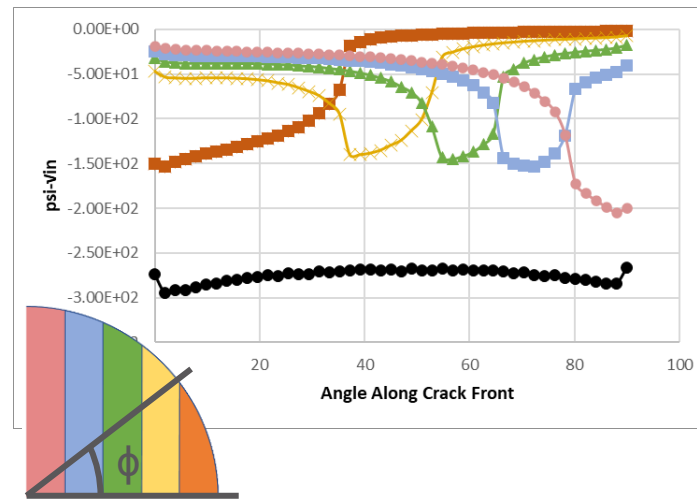
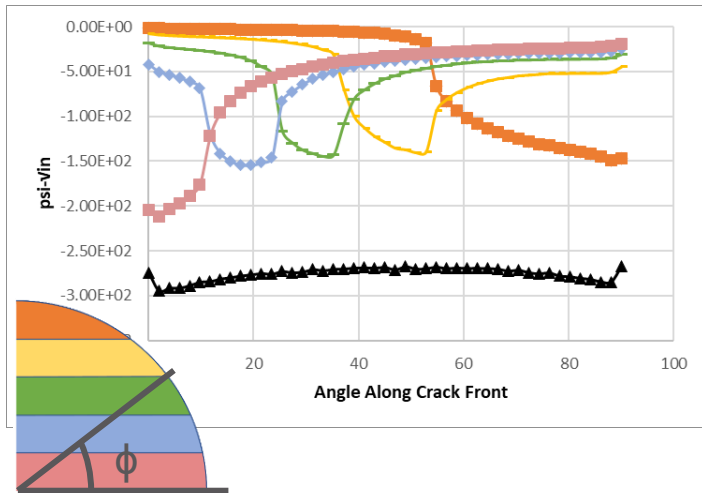
# Questions

Area of confidence



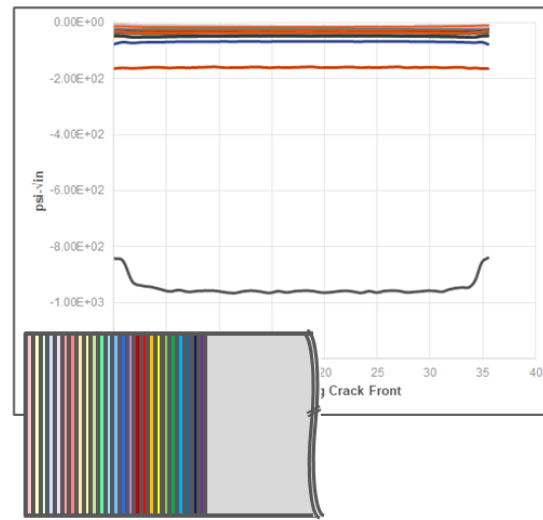
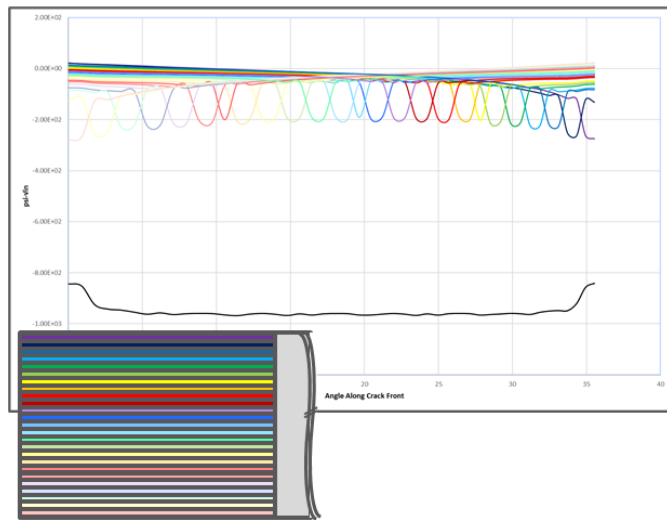
# Unit RS effects on SIF

- ❑ Applied a unit crack face traction on each color segment
  - ❑ 0.05" quarter circular crack with five 0.01" segments
- ❑ Extracted SIF of crack front
- ❑ Superposition holds for crack face traction
- ❑ SIF is higher at the location the RS is applied



# Unit RS effects on SIF

- ❑ Applied a unit crack face traction on each color segment
  - ❑ 0.35" straight thru-crack with 0.01" vertical and horizontal segments
- ❑ Extracted SIF of crack front
- ❑ Superposition holds for crack face traction
- ❑ SIF is highest at the location the RS is applied



- 20% of total SIF comes from 0.32-0.35 inch segments
- 50% of total SIF comes from 0.25-0.35 inch segments

