Predicting Total Fatigue Life
(Crack Initiation + Crack Propagation)

SAE FD&E Semi-Annual Meeting
At Iowa State (Ames, IA) -25 April 2013
(Prepared by Tom Cordes)

Total Fatigue Life: Crack Initiation + Crack Propagation Analysis

April 25th

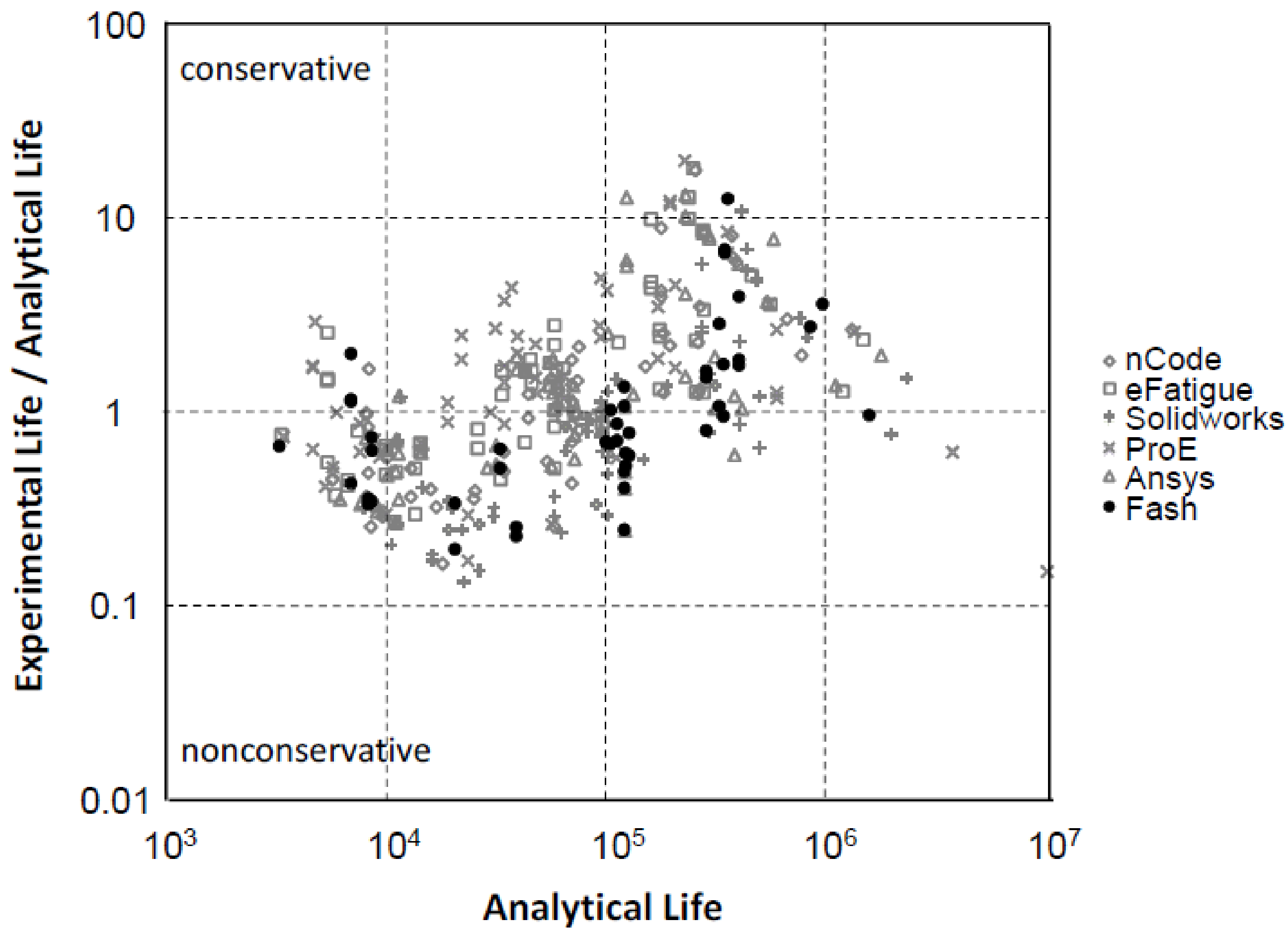
7:30 – 8:00 am	Registration – 2121 Martin Hall @ Iowa State University
8:00	Welcome address
8:15- 9:15	Honorary Member Talks
	Charlie Sieck from CAT and Phil Dindinger formerly of Element
Break	
9:30 – 12:00	**Total life Project – Testing & Analysis Update, Discussion**
	Tom Cordes (nCode), Eric Johnson (Deere), Hayley Brown and Mark Andrews (CAT)
12:00 – 1:00	**Lunch – On your own**

I'm not here as a software salesman or promoter. I've been doing fatigue analysis and testing for 43 years and I like what I do. Using all kinds of different tools, I've spent 8 years doing fatigue analysis and testing on the F-15 and F-4 Fighter Aircraft, 24 years working on all of John Deere's equipment ranging from Log Skidders to Lawn Mowers, and 11 years working on Military Vehicles, Automotive Driveline Components, Nuclear Pressure Vessel Equipment, etc. Over those 43 years I've observed one thing in all those industries that has gotten me very involved this effort. When a (multi)million dollar production problem can't be solved with just S-N, crack initiation or crack propagation analysis alone, those two (competitive) disciplines come together, and more often then not, a solution is found.

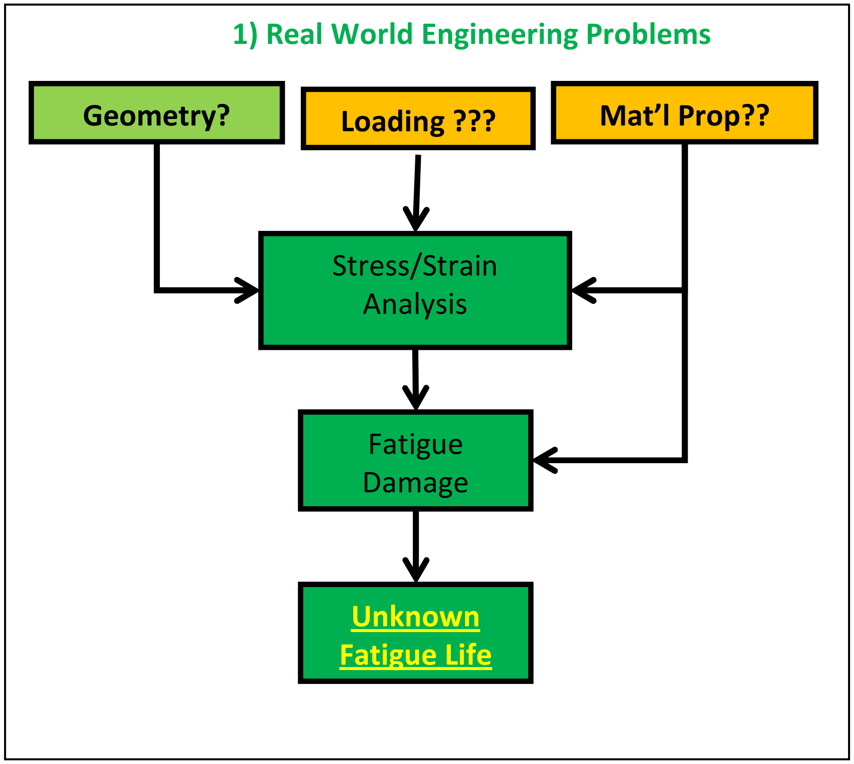
Fatigue Life: Previous SAE FD&E Crack Initiation Analysis/Test Effort

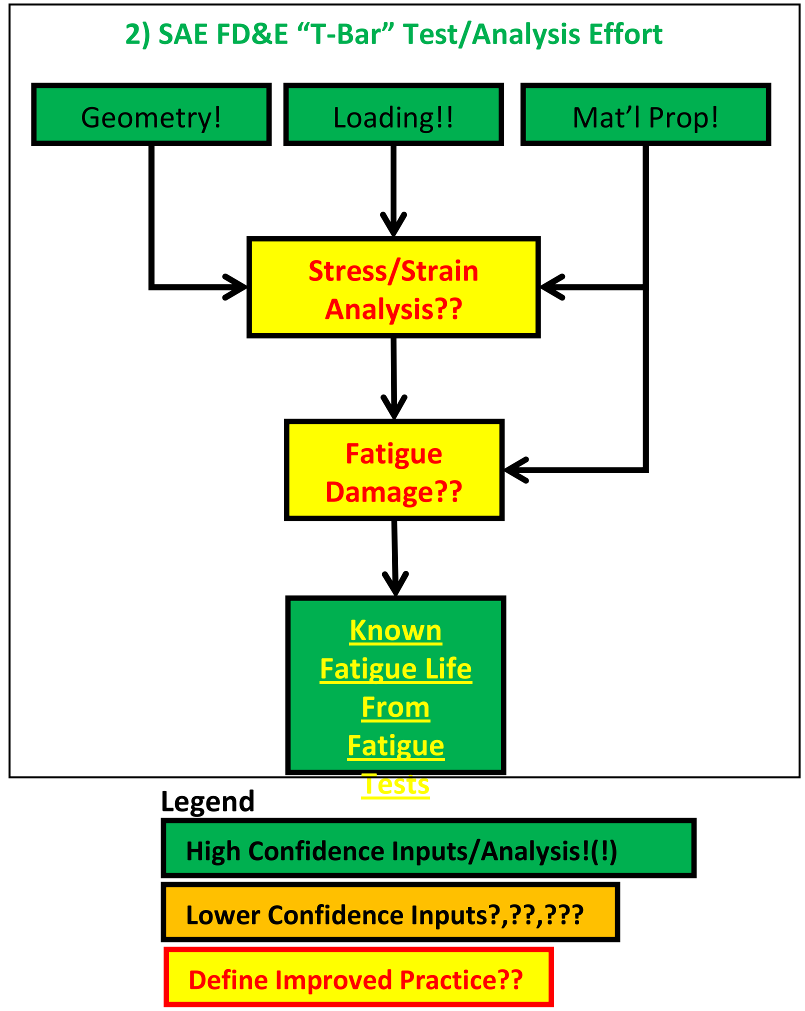
Previous SAE FD&E Analysis to Test Correlation Effort Results

A brief summary of the fatigue theories and strategies employed by the various software packages used to compute fatigue lives is given below. A common feature of all of the analysis is that they used what may be termed the strain-life method. Commonality ends there. They all used different notch rules and fatigue damage models.



Total Fatigue Life: Crack Initiation + Crack Propagation Analysis

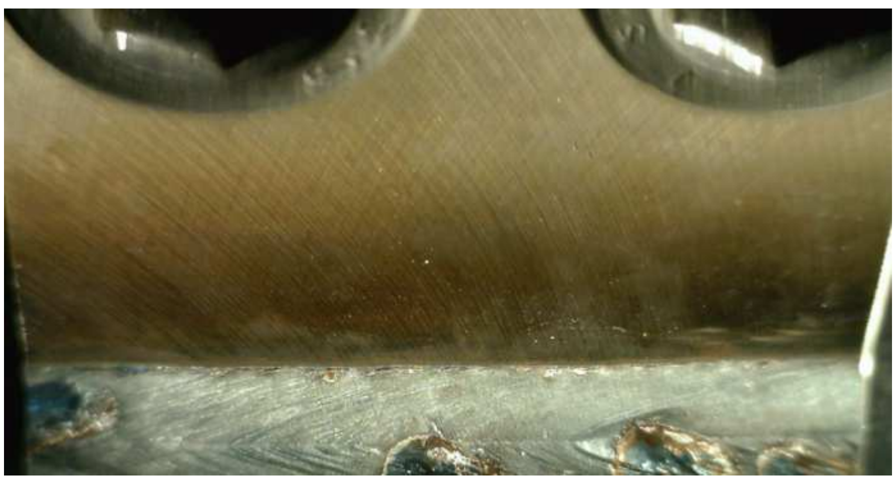




This effort is using "very well defined/controlled analysis inputs" to address an engineering problem to validate (or not) a potential "Total Fatigue Life Prediction Improved Practice"

Total Fatigue Life: Crack Initiation + Crack Propagation Analysis

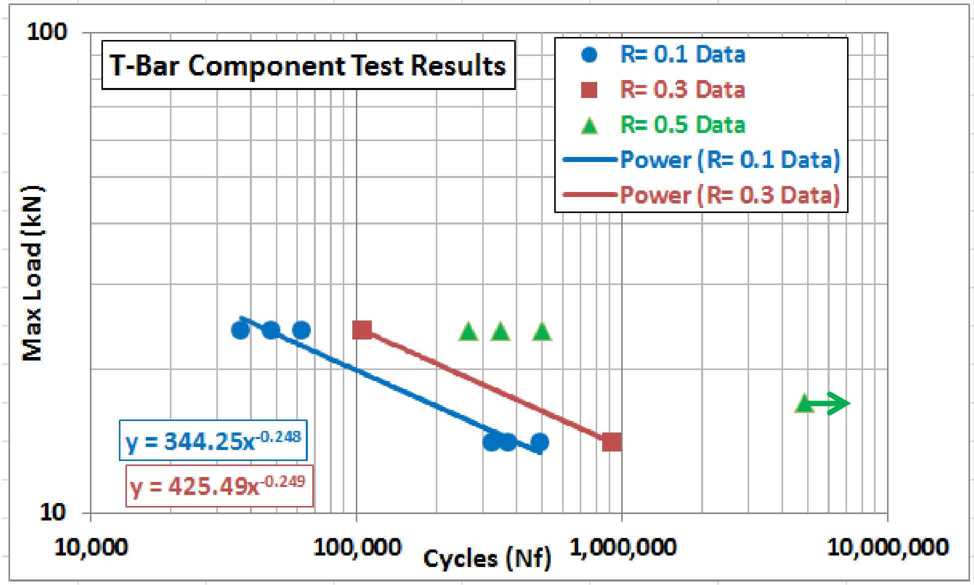
Play Three Video’s:

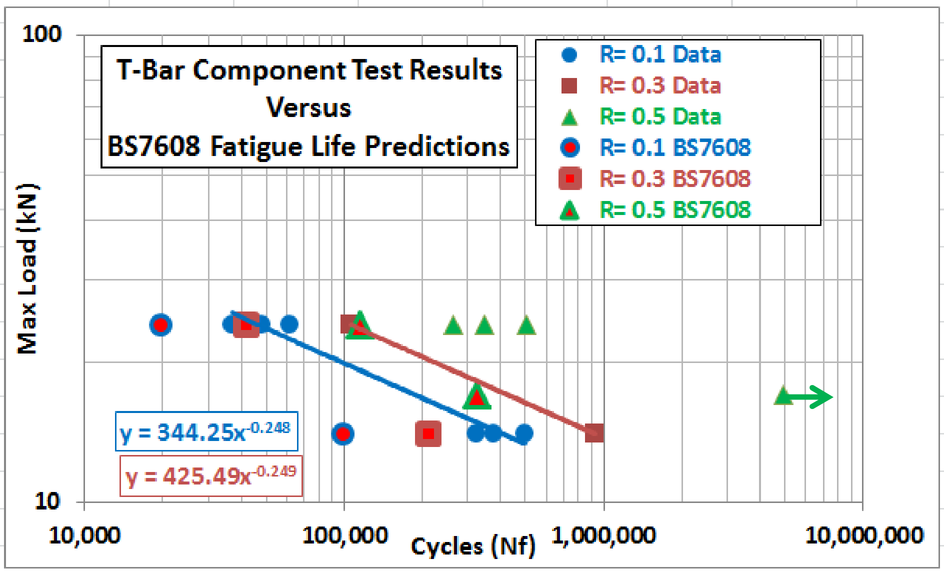


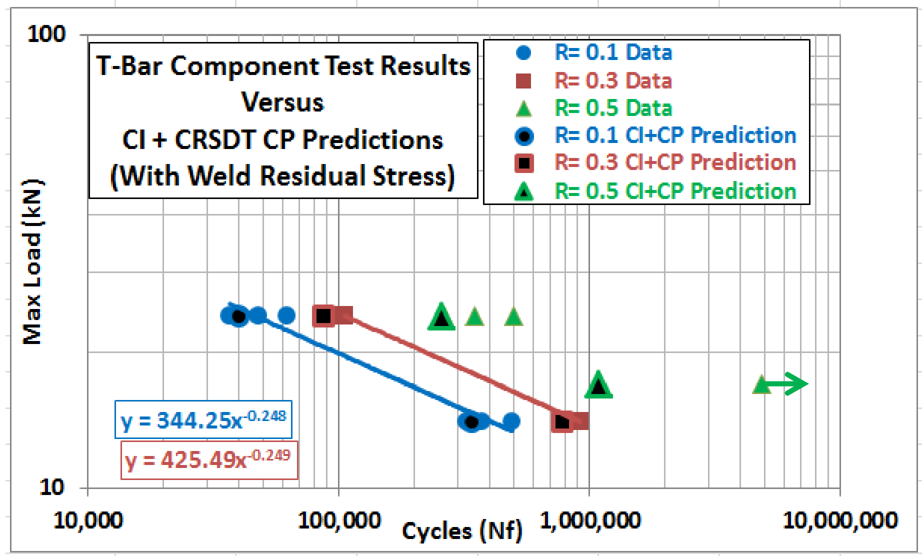
Total Fatigue Life: Crack Initiation + Crack Propagation Analysis

Max Ld kN	R Ratio	Test Cycle	Test Counter Cycles	Weld Sample: Run-Position
24	0.1	Constant Amplitude	36,895	Hand Weld
24	0.1	Constant Amplitude	48,160	2-2
24	0.1	Constant Amplitude	62,047	6-3
24	0.3	Constant Amplitude	105,522	4-2
24	0.5	Constant Amplitude	262,628	4-3
24	0.5	Constant Amplitude	349,002	6-4
24	0.5	Constant Amplitude	503,441	5-?
14	0.1	Constant Amplitude	325,579	5-3
14	0.1	Constant Amplitude	375,813	3-4
14	0.1	Constant Amplitude	494,456	3-3
14	0.3	Constant Amplitude	922,658	3-1
17	0.5	Constant Amplitude	4,900,000 NC*	5-1
24	0.1/0.5	Block Loading	138,421	4-1

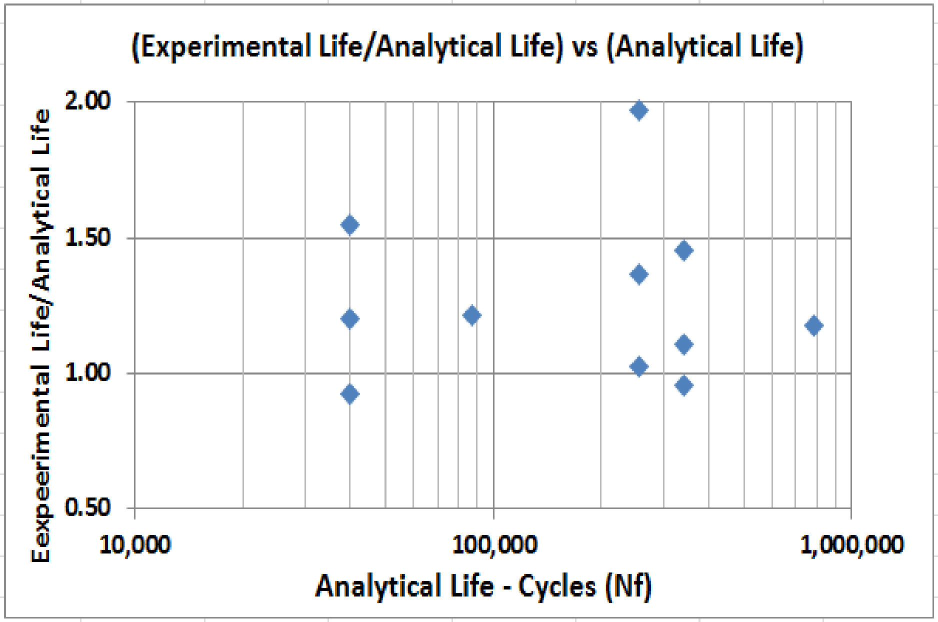
*Note: No crack growth observed visually

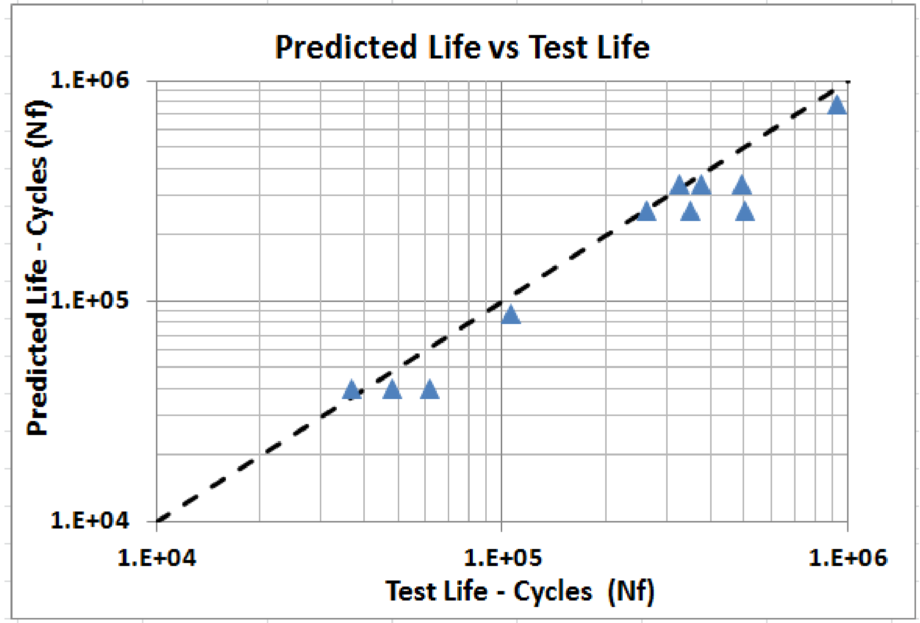


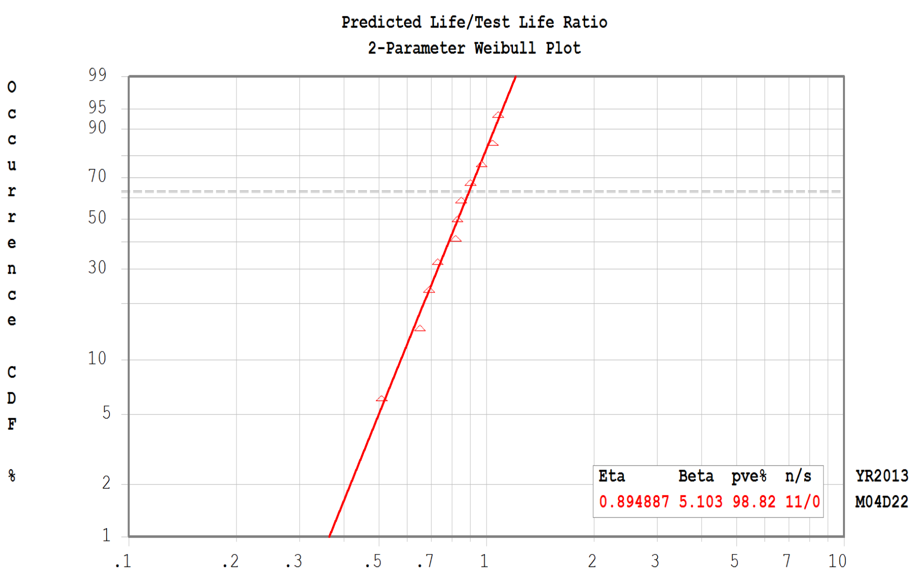


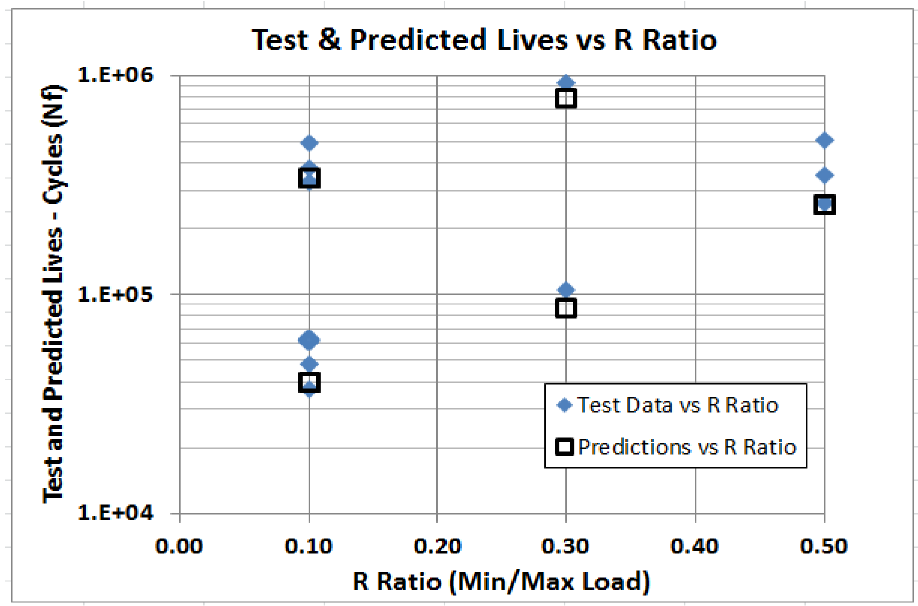


Total Fatigue Life: Crack Initiation + Crack Propagation Analysis



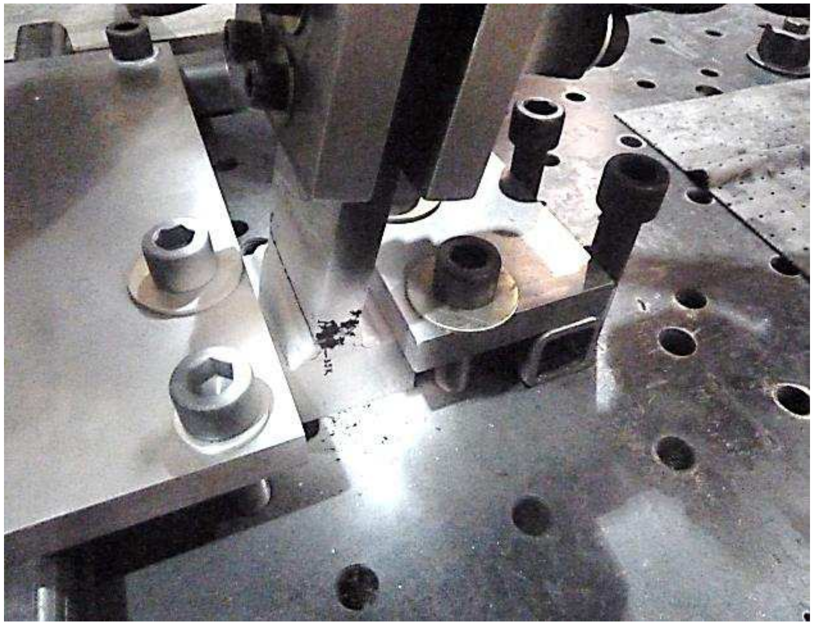


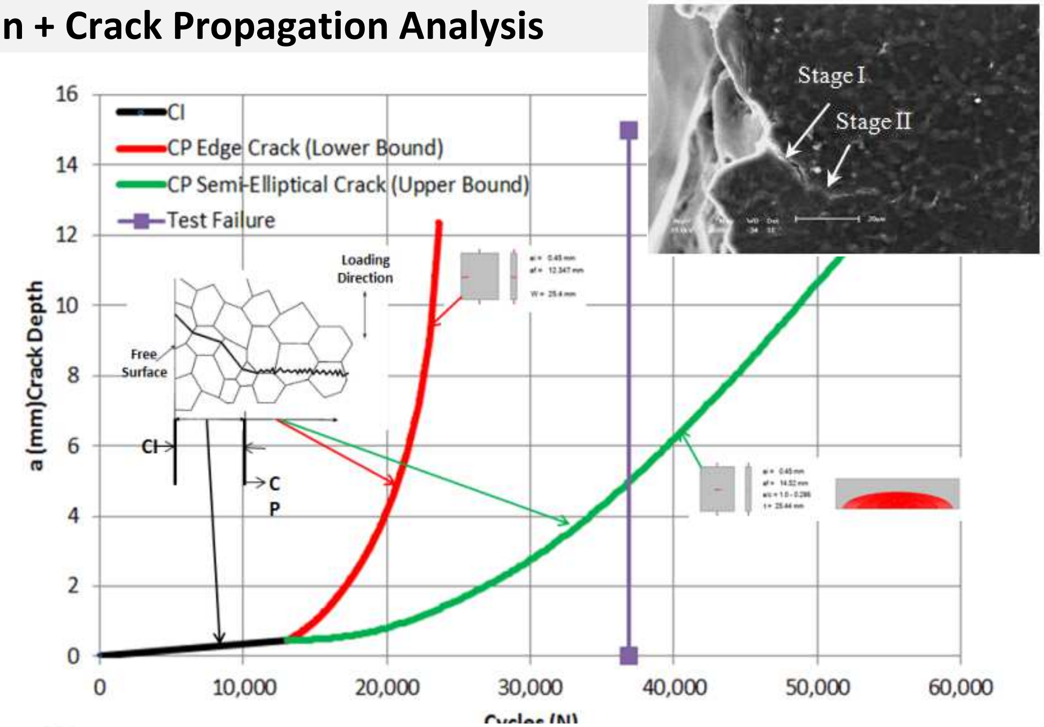


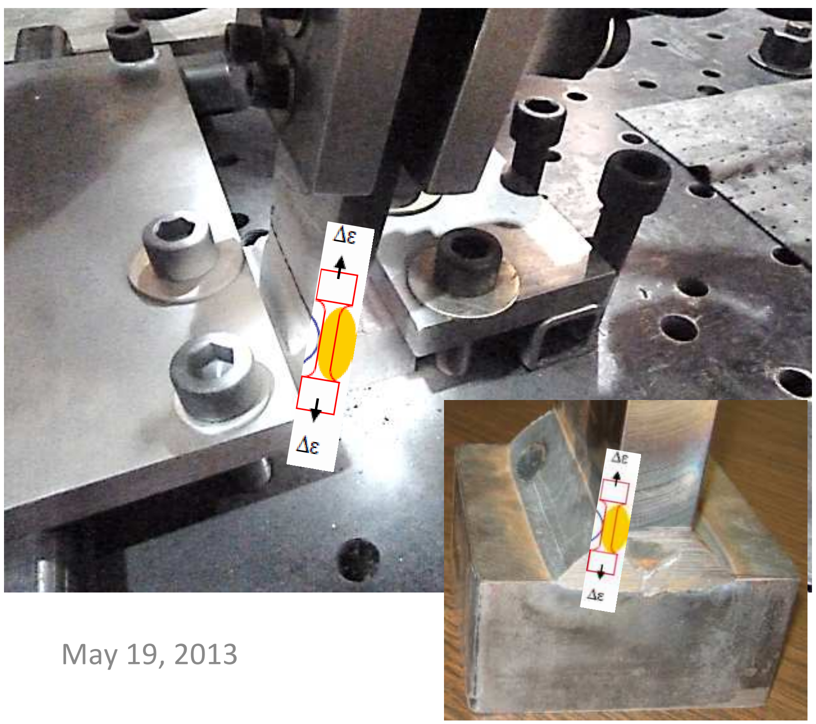


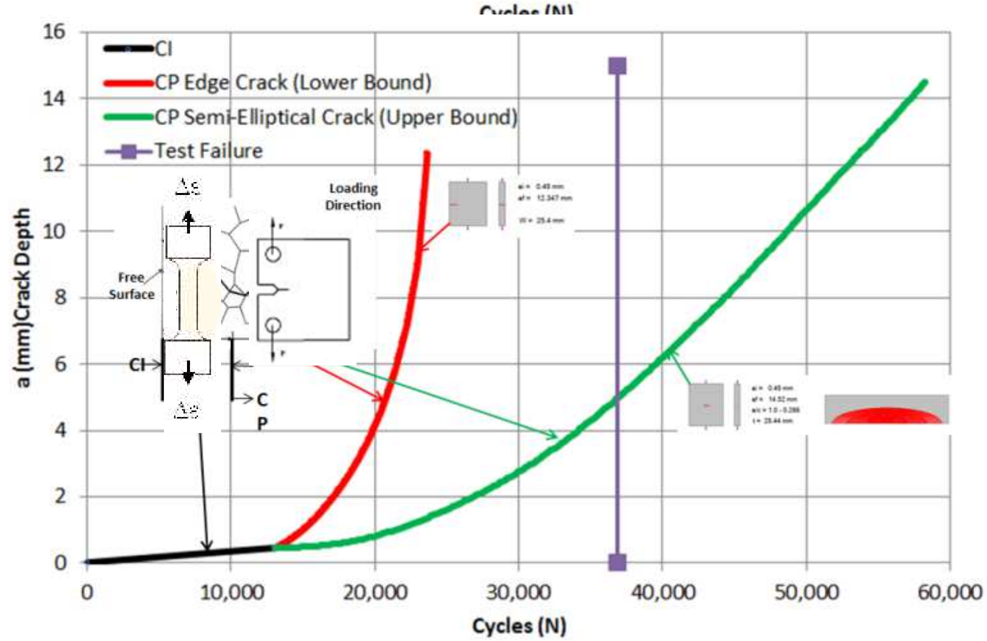
RF

Total Fatigue Life – Combining the Crack Initiation + Crack Propagation Analysis

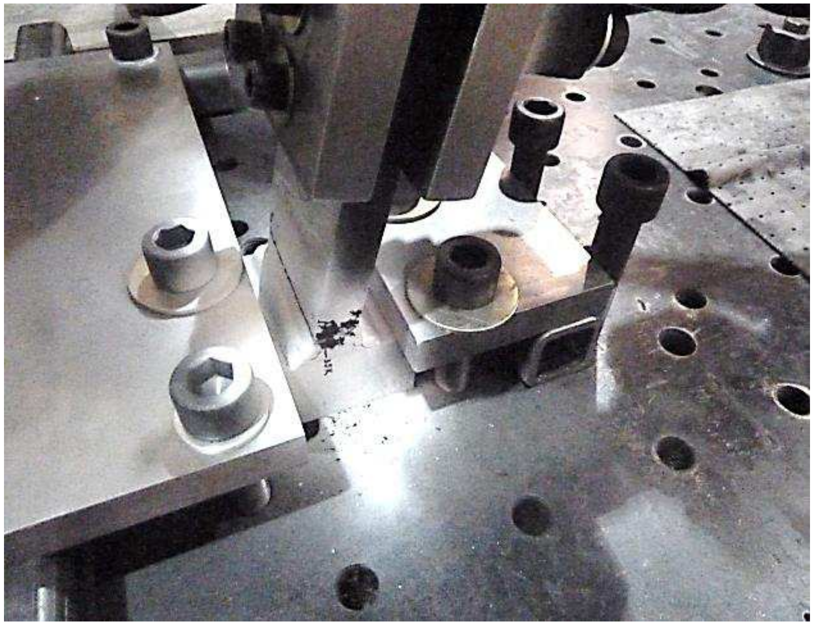


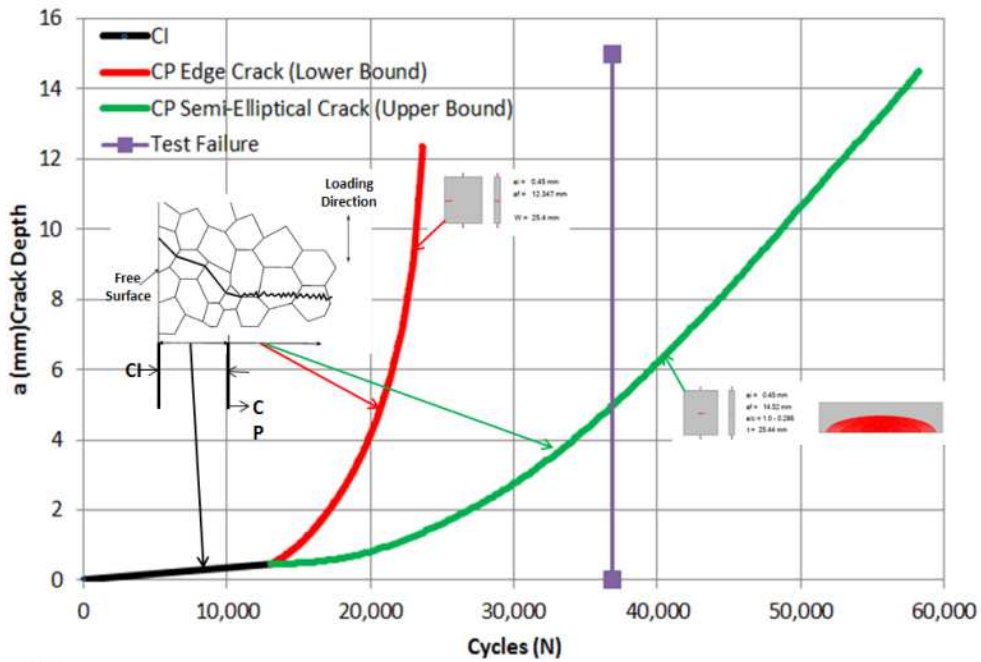


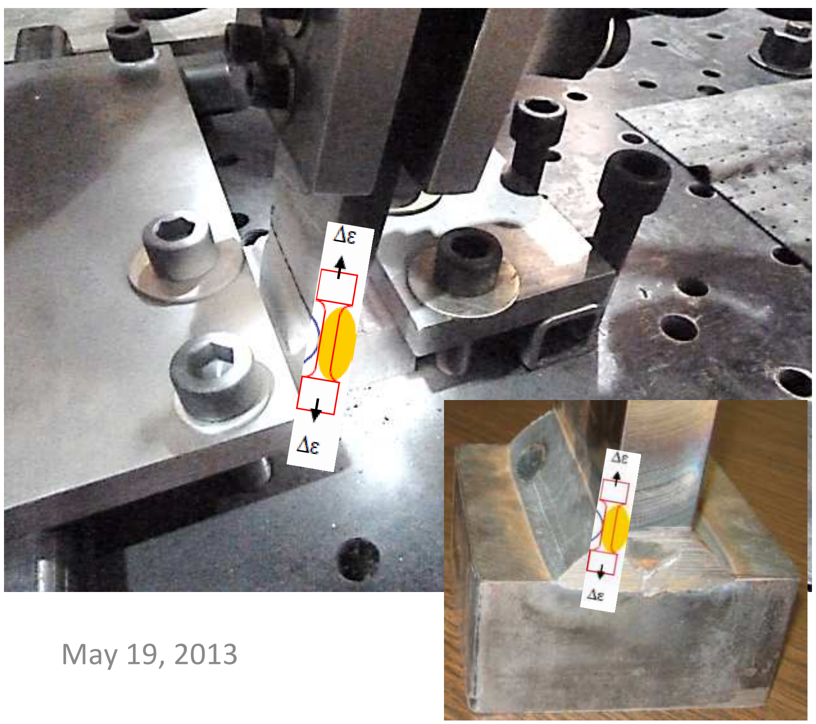


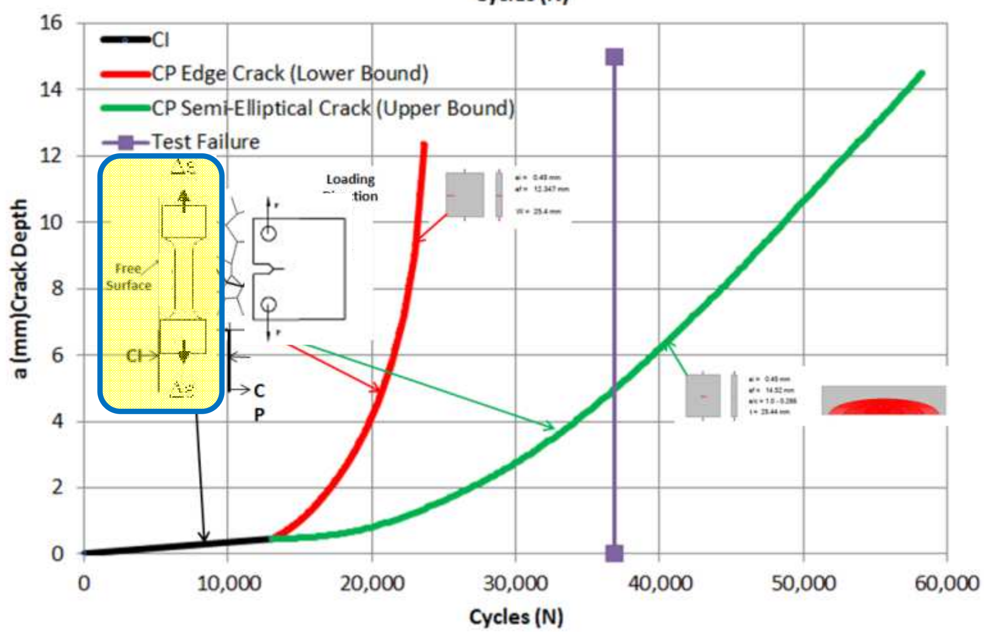


Total Fatigue Life – First: Address Just Crack Initiation Analysis



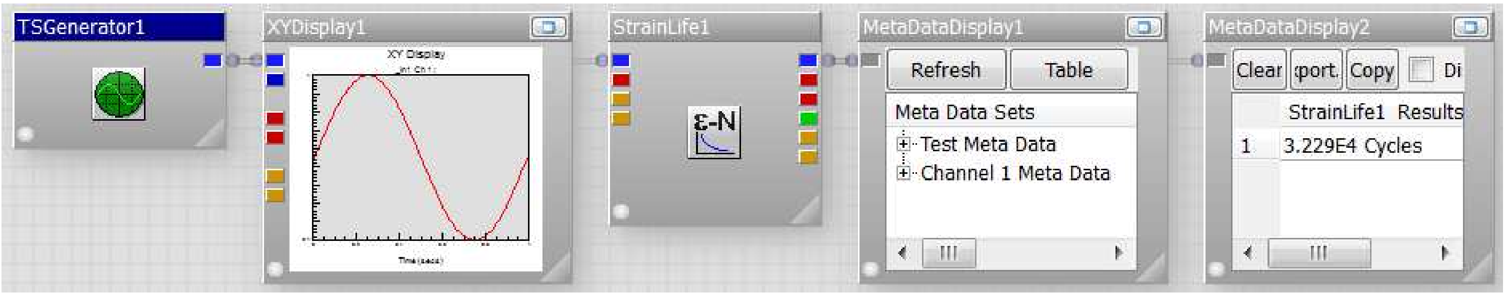






Crack Initiation Analysis Methodology/Process

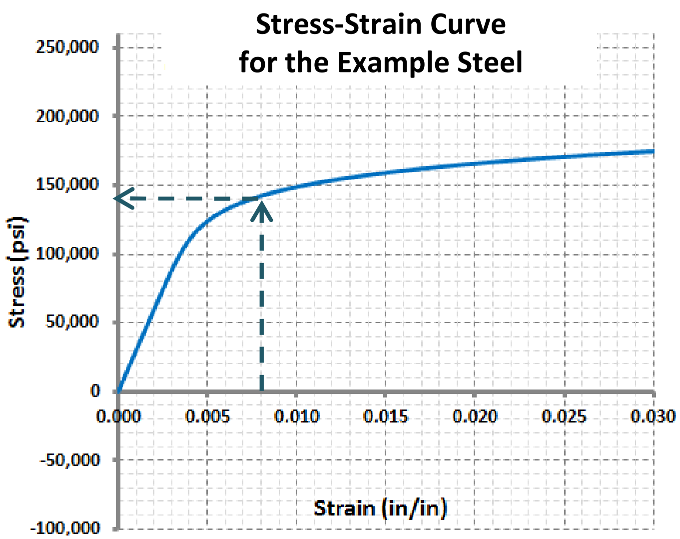
1) The crack initiation fatigue analysis methodology/process used to analyze the SAE T-Bar Test Specimen is the local strain approach applying Neuber's Rule to convert linear elastic FEM stresses and strains to the material's nonlinear elastic-plastic stress/strain behavior. Neuber's Rule tracks those stresses and strains through the load cycle applied. **As will be shown in the following slides, the actual material cycle defined by Neuber's Rule is much different then that calculated by the linear elastic FEM.** Neuber's Rule is the fatigue community's generally accepted practice for addressing the physics of this (necessary) elastic analysis to real world material behavior conversion issue. It is utilized by most fatigue experts, such as Darrell Socie at the University of Illinois, Gregory Glinka at the University of Waterloo, Ontario, CA., etc.
2) The results of that Neuber analysis is then taken into a Smith-Watson-Topper (SWT) fatigue damage model to properly account for the mean stress of the nonlinear elastic-plastic stress/strain cycle identified and calculate the crack initiation fatigue life. **The SWT methodology is the fatigue community's generally accepted practice for accounting for the different mean stresses of real world fatigue cycles.** It is utilized by industry wide recognized fatigue experts, such as Darrell Socie at the University of Illinois, Gregory Glinka at the University of Waterloo, Ontario, CA. etc.
3) **Because that analysis methodology is numerically intensive due to the many iterative solutions necessary to account for real world material nonlinear behavior,** the analysis was completed using the HBM-nCode software "Glyphworks flo":



4) All the necessary inputs for the analysis are documented in the following slides. However to "provide details of the methodology" (in addition to using the "flo") a full "example" analysis was worked through (for another steel) and follows. All equations are documented (and plotted) as the methodology steps through the process to calculate the fatigue life. Please note that the units used in this example (only) are psi.

Crack Initiation Analysis Methodology/Process

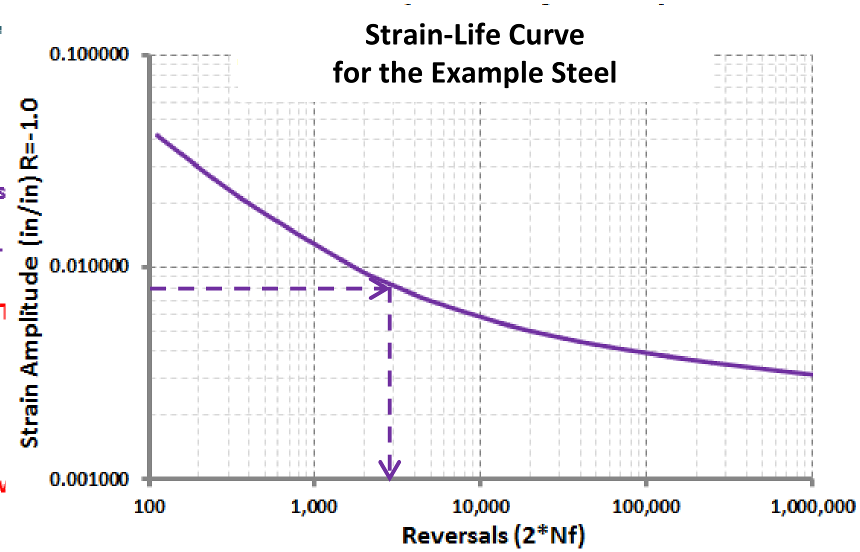
Develop the **"Iterative"** Smith-Watson-Topper (SWT) versus Fatigue Life (Nf) relationship/curve for the example steel. This is accomplished by "merging" the stress-strain curve with the strain life curve as shown below. **The SWT vs Nf relationship/curve is independent of R ratio and thus can be used to determine the fatigue life for any properly defined cycle (per the Neuber analysis technique shown on the preceding slide).**

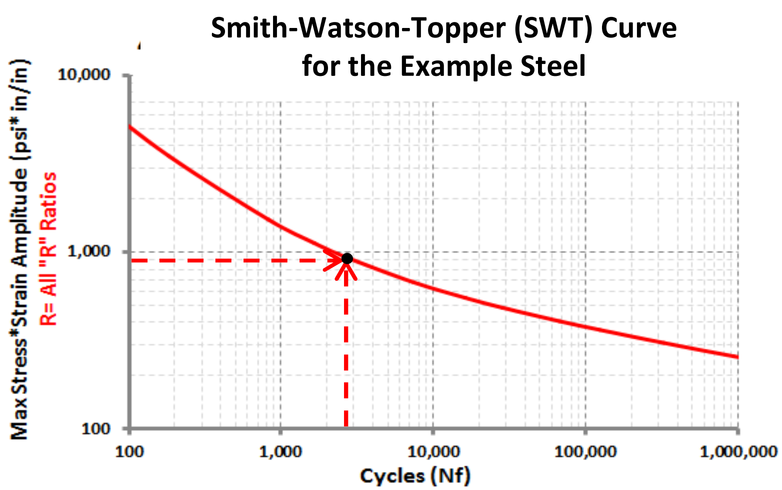


For a selected R=-1.0 strain value (ε) obtain it's maximum stress value (σmax) from the cyclic stress strain curve .

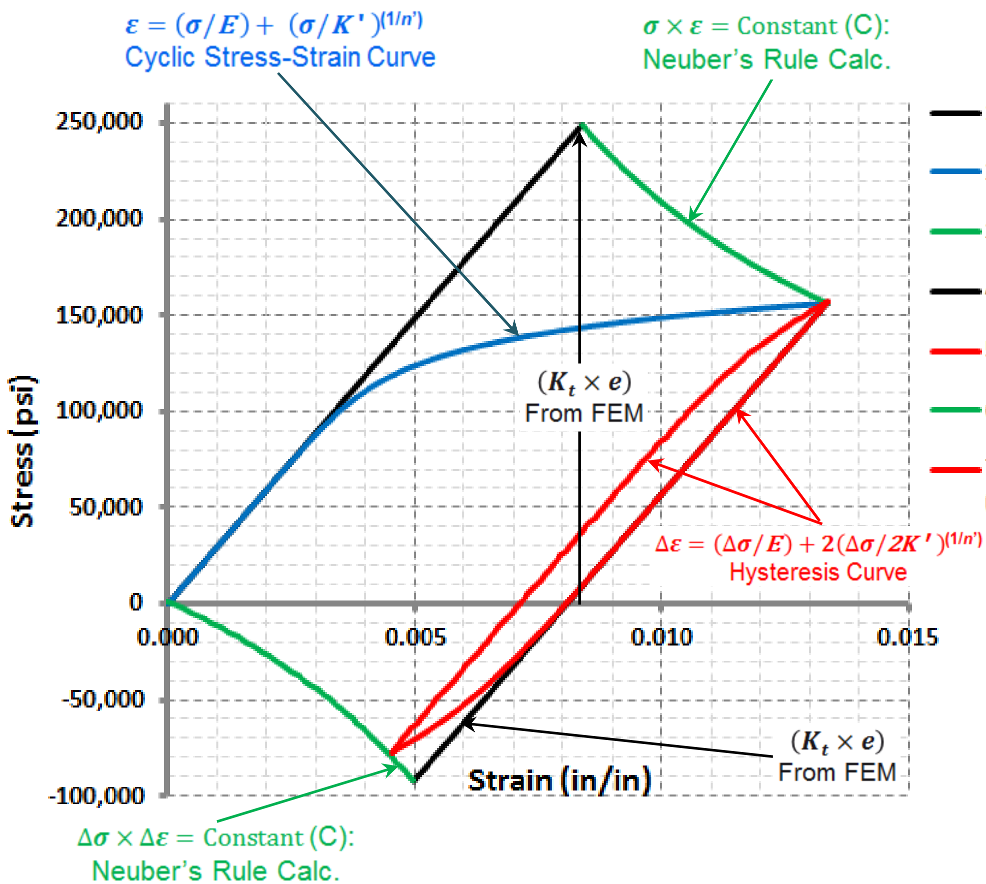
For that same strain value (ε), because for R=–1.0, $\varepsilon = \Delta\varepsilon/2$ (it's strain amplitude), obtain it's fatigue life (2*Nf) from the strain-life curve.

From the above, calculate the SWT parameter : ($\sigma max \times \Delta\varepsilon/2$) and associate it with it's life Nf. From that, plot the point ● to define one point of the SWT vs Nf curve as shown below. Repeat as necessary to fill out the full SWT v Nf curve.





Convert the linear-elastic FEM stress-strain values to the actual steel nonlinear elastic-plastic stress-strain values. During that conversion, track those stresses and strains through the loading and then the unloading of the applied cycle to define the cycle that does the fatigue damage (see the closed red loop shown below). Obtain the peak and valley stress-strain coordinates that define that cycle from that analysis. That actual analysis for the example steel is shown in the following slides.



- 1) FEM Elastic Strain Loading $(K_t \times e)$: From FEM
- 2) Mat'l 1st Loading $\varepsilon = (\sigma/E) + (\sigma/K')^{(1/n')}$: Cyclic Stress-Strain Curve
- 3) FEM to Mat'l Neuber's Rule Calc. $\sigma \times \varepsilon =$ Constant (C)
- 4) FEM Elastic Strain Unloading $(K_t \times e)$: From FEM
- 5) Mat'l Strain Hysteresis Unloading $\Delta\varepsilon = (\Delta\sigma/E) + 2(\Delta\sigma/2K')^{(1/n')}$
- 6) FEM to Mat'l Neuber's Rule Calc. $\Delta\sigma \times \Delta\varepsilon =$ Constant (C)
- 7) Mat'l Strain Hysteresis Loading $\Delta\varepsilon = (\Delta\sigma/E) + 2(\Delta\sigma/2K')^{(1/n')}$ (To Complete The Cycle)

Neuber's Rule

$(K_t \times S) \times (K_t \times e) = \sigma \times \varepsilon$ (General Equation)

$S = e \times E$

$(K_t \times e \times E) \times (K_t \times e) = \sigma \times \varepsilon$

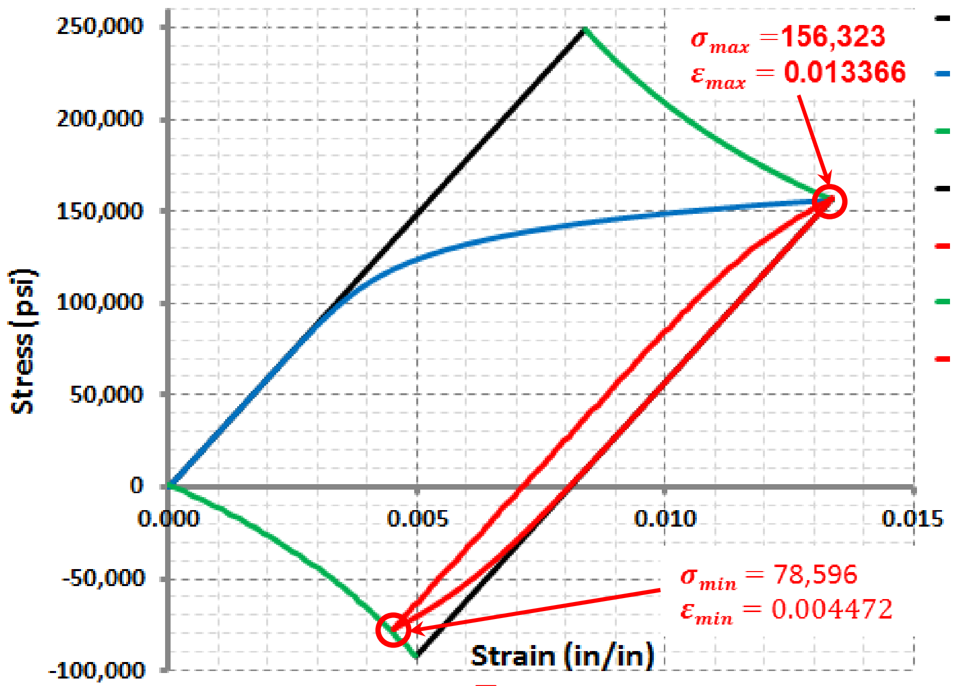
Equation Manipulation To Do FEM Analysis

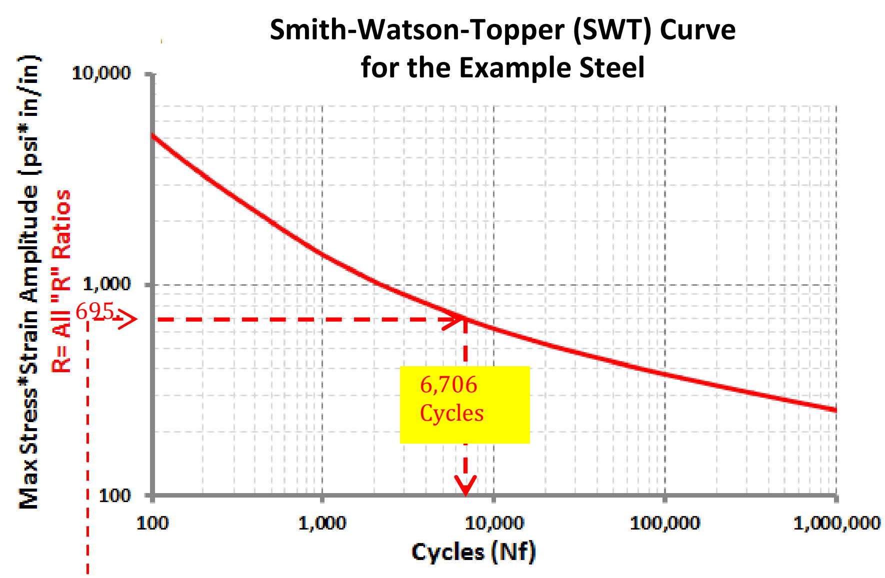
$(K_t \times e)^2/E = \sigma \times \varepsilon$ (Analysis Equation)

$(K_t \times \Delta e)^2/E = \Delta\sigma \times \Delta\varepsilon$ (Analysis Equation)

Crack Initiation Analysis Methodology/Process

Merging the results of the analysis defined in the previous two slides, the fatigue life prediction is made as shown below:





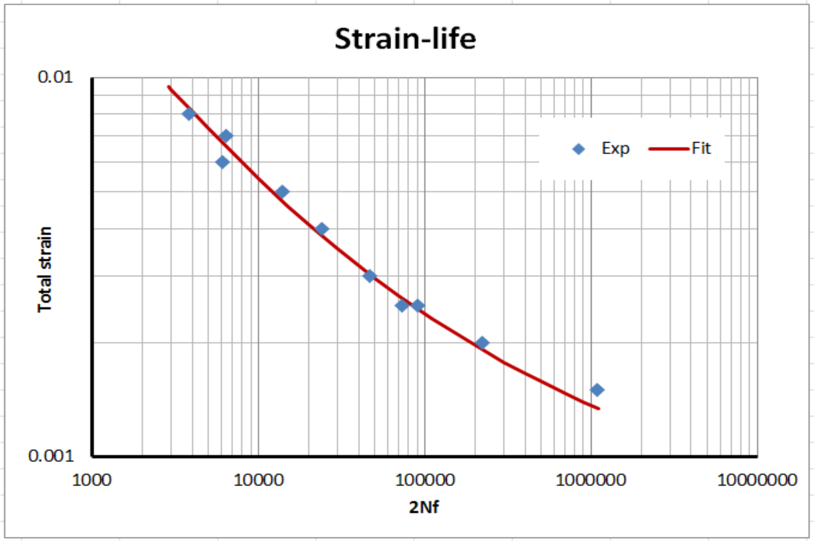
$\sigma_{max} = 156,323$

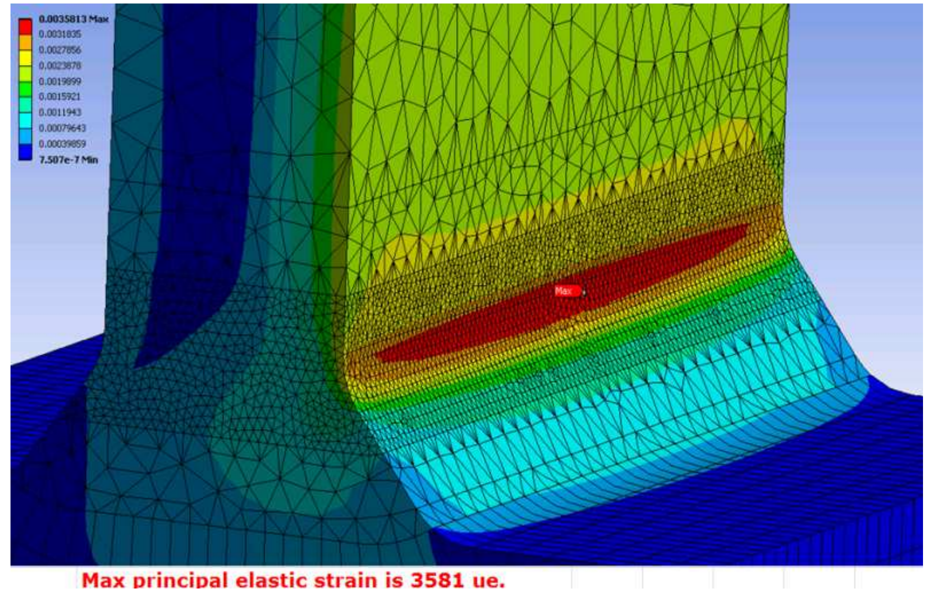
$\Delta\varepsilon/2 = (0.013366 - 0.004472)/2 = 0.004447$

$\sigma_{max} \times \Delta\varepsilon/2 = 695.$

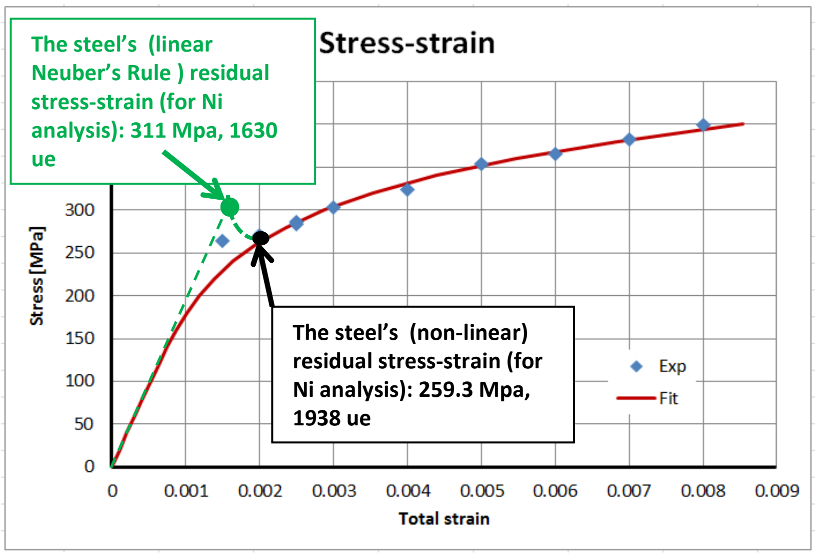
The crack initiation fatigue life for this example problem is 6,706 cycles

Crack Initiation Analysis – Setup the Crack Initiation Analysis for the T-Bar (All Necessary Input Information)





At 24 kN



Because the weld toe residual stress profile is not yet available for the T-Bar a (non-linear) surface residual stress of 0.80 times the cyclic yield stress was assumed : Sres=0.80 X 324.12 Mpa= 259.30 Mpa (at 1938 ue. This point is shown on the stress-strain curve on the plot to the left)

However, because the FEM of the T-Bar was a linear elastic analysis, the non-linear residual strain needed to be converted back to its equivalent linear elastic value so it could be correctly added to the FEM elastic values. That Neuber Rule analysis technique used to do that was describe on the previous slides 9 thru 12. Those elastic residual stress coordinates are: 311.0 Mpa (at 1630 ue). This point is shown on the stress-strain curve on the plot to the left)

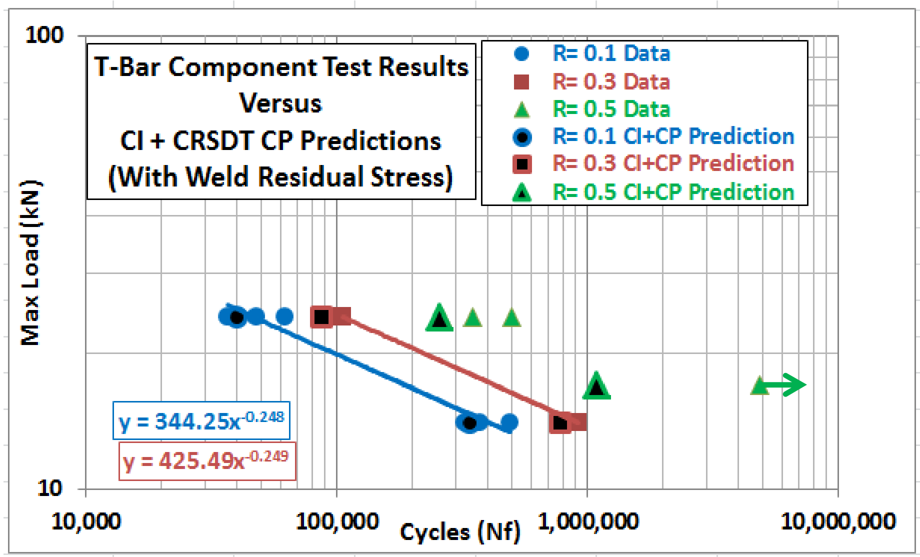
E	Sys	K'	n'	sf'	ef'	b	c
190786	324.12	991.4	0.1799	1025.9	0.7627	-0.1132	-0.5837

Crack Initiation

The crack initiation segment of the fatigue lives were calculated from the information just provided

Max Ld kN	R Ratio	Test Cycle	Test Counter Cycles	Weld Sample: Run-Position
24	0.1	Constant Amplitude	36,895	Hand Weld
24	0.1	Constant Amplitude	48,160	2-2
24	0.1	Constant Amplitude	62,047	6-3
24	0.3	Constant Amplitude	105,522	4-2
24	0.5	Constant Amplitude	262,628	4-3
24	0.5	Constant Amplitude	349,002	6-4
24	0.5	Constant Amplitude	503,441	5-?
14	0.1	Constant Amplitude	325,579	5-3
14	0.1	Constant Amplitude	375,813	3-4
14	0.1	Constant Amplitude	494,456	3-3
14	0.3	Constant Amplitude	922,658	3-1
17	0.5	Constant Amplitude	4,900,000 NC*	5-1
24	0.1/0.5	Block Loading	138,421	4-1

*Note: No crack growth observed visually



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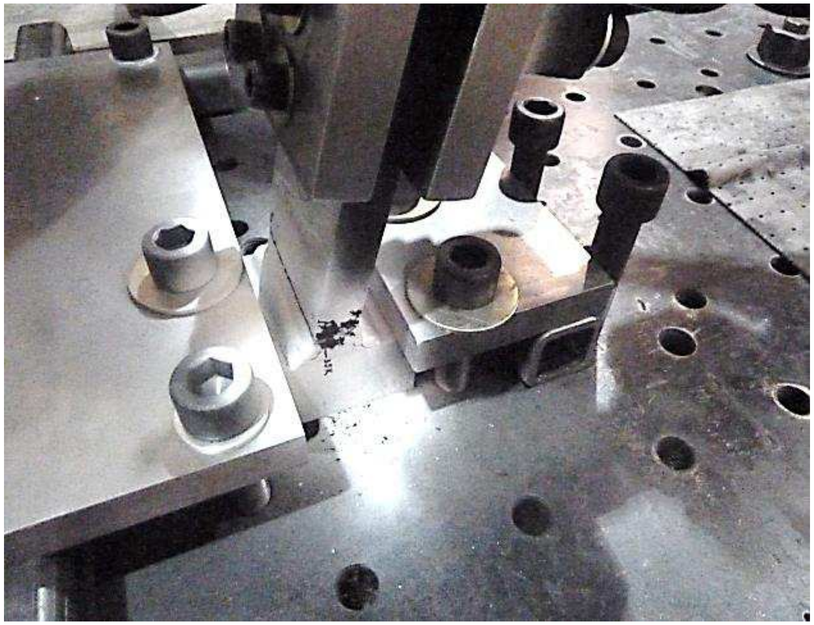
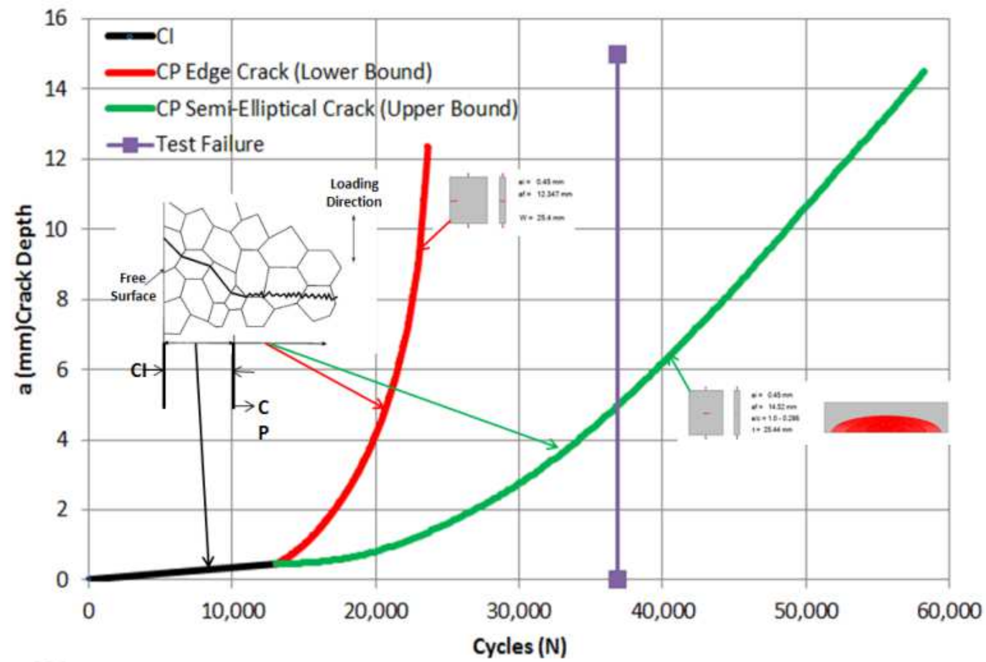
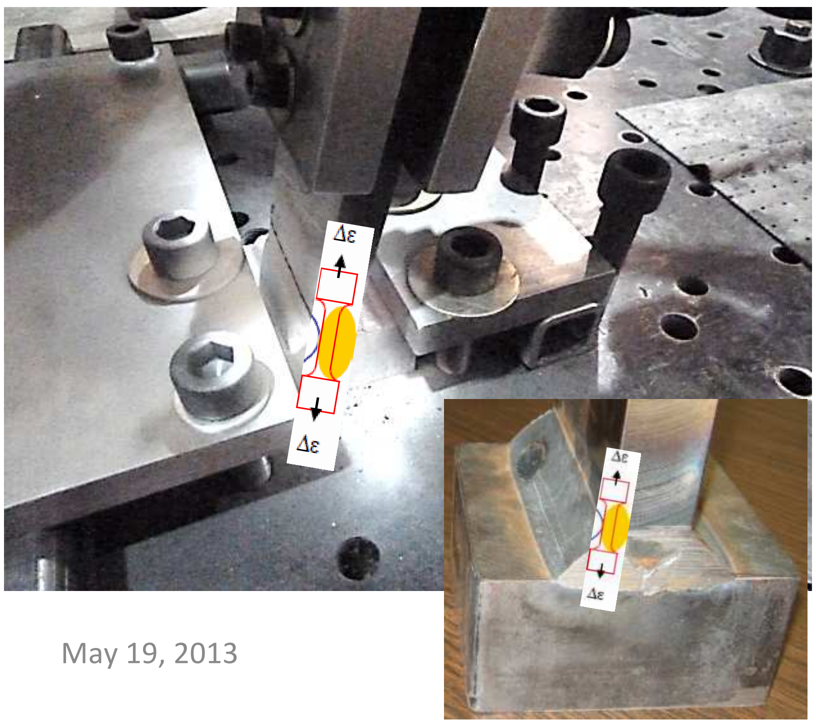
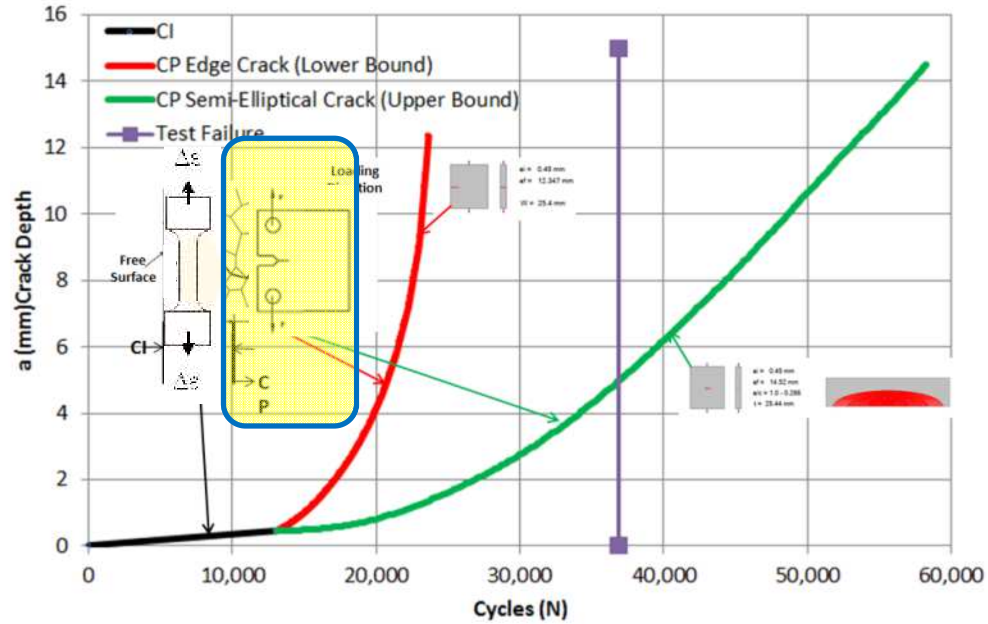
Total Fatigue Life – Second: Address Just Crack Propagation Analysis









Adding Universal Weight Function (UWF) Stress Intensity File (SIF) Capability
(Get a More Representative Stress Intensity Solution Directly From the Actual Geometry FEM Stress Distribution)

Some Other SIF Approaches

(a similar geometry stress intensity factor distribution is picked from a library of solutions)

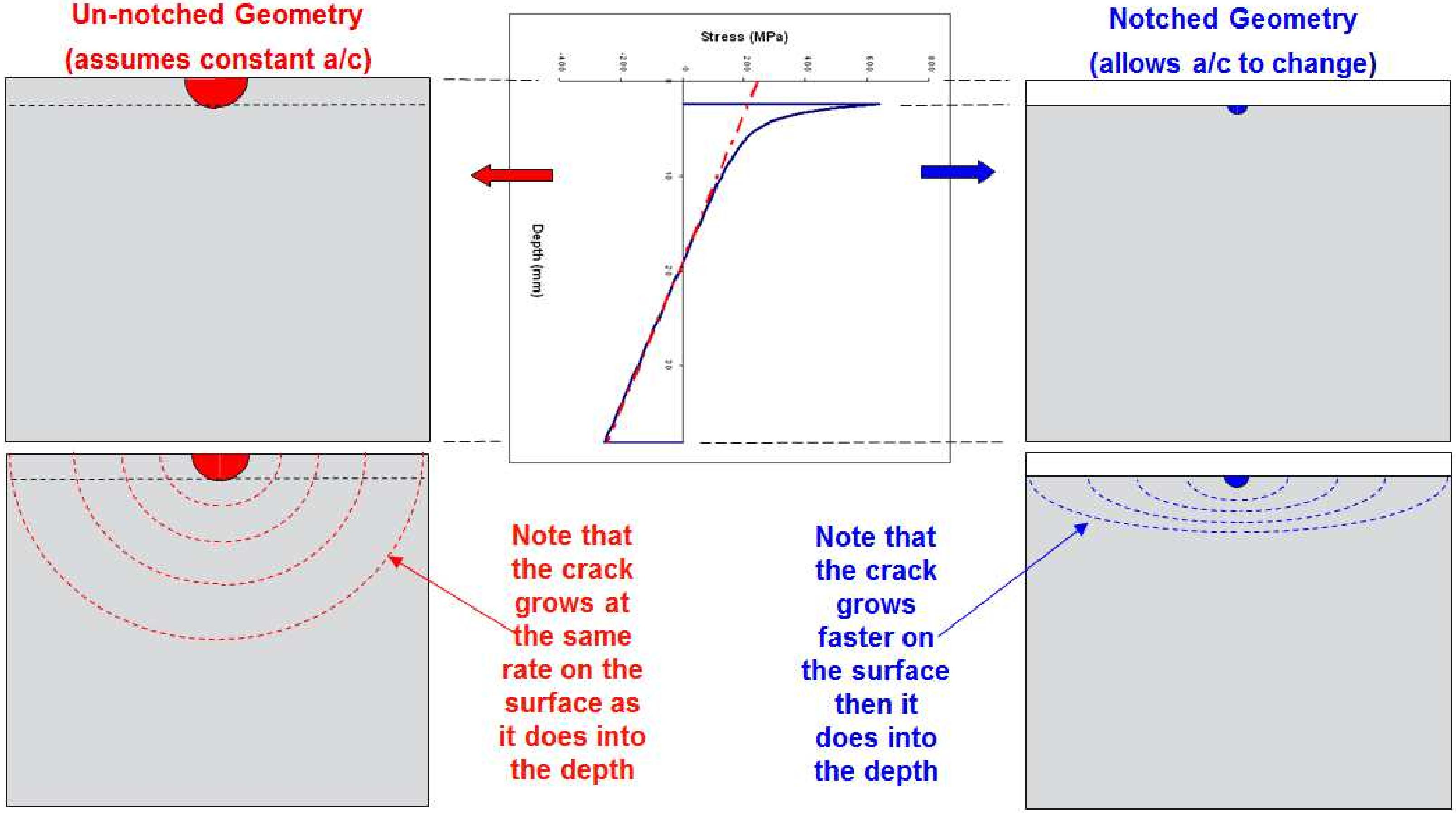
Enhancement - Used UWF

(the stress intensity factor is calculated from a FEM distribution as the crack grows)
(at the depth and at the surface)

Stress Distribution

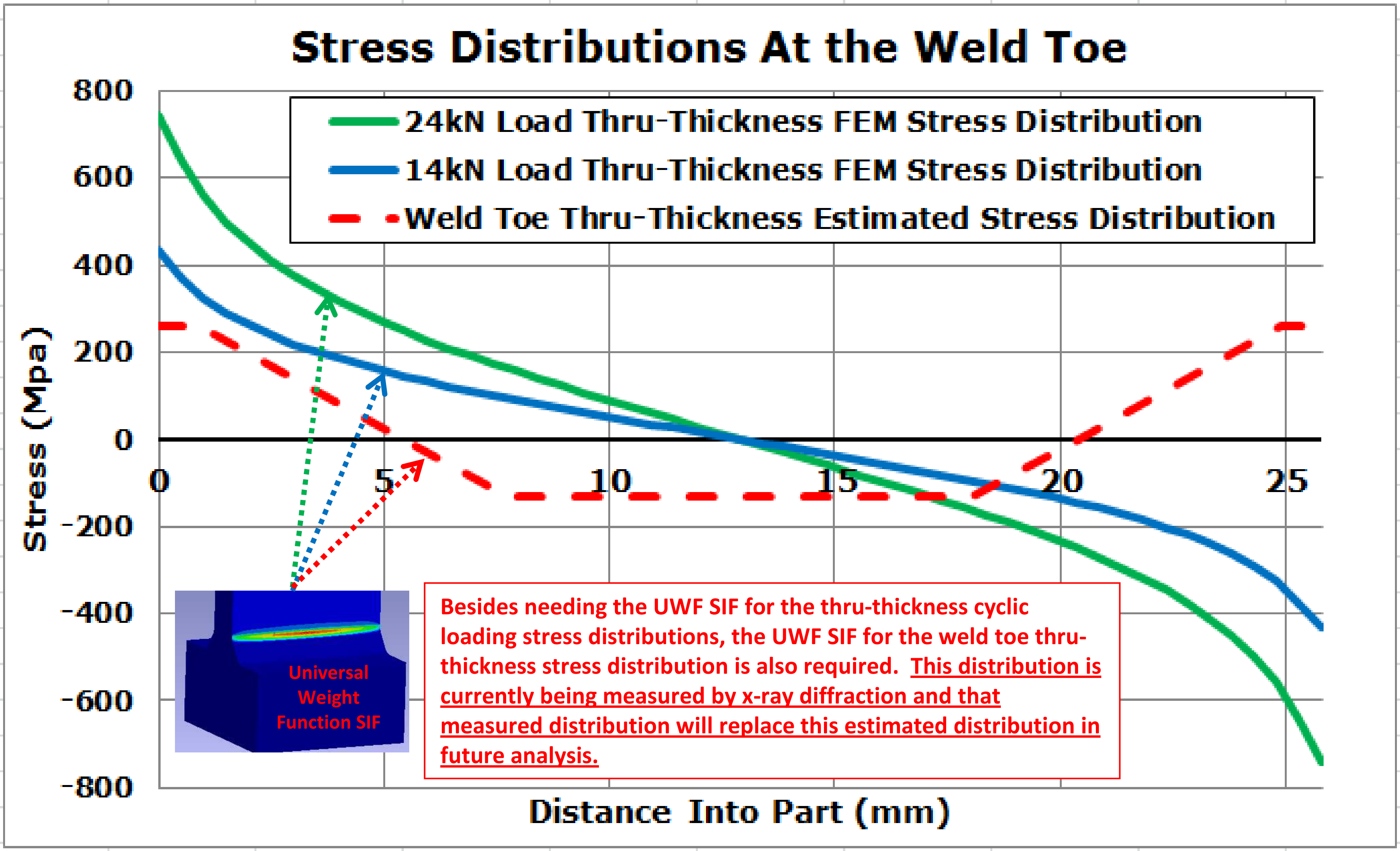
Un-notched Geometry
(assumes constant a/c)

Notched Geometry
(allows a/c to change)



Total Fatigue Life – Summary of Enhancement Used in the Crack Propagation Analysis

Added Universal Weight Function (UWF) Stress Intensity File (SIF) Capability
(Get a More Representative Stress Intensity Solution Directly From the Hardware FEM Stress Distribution)



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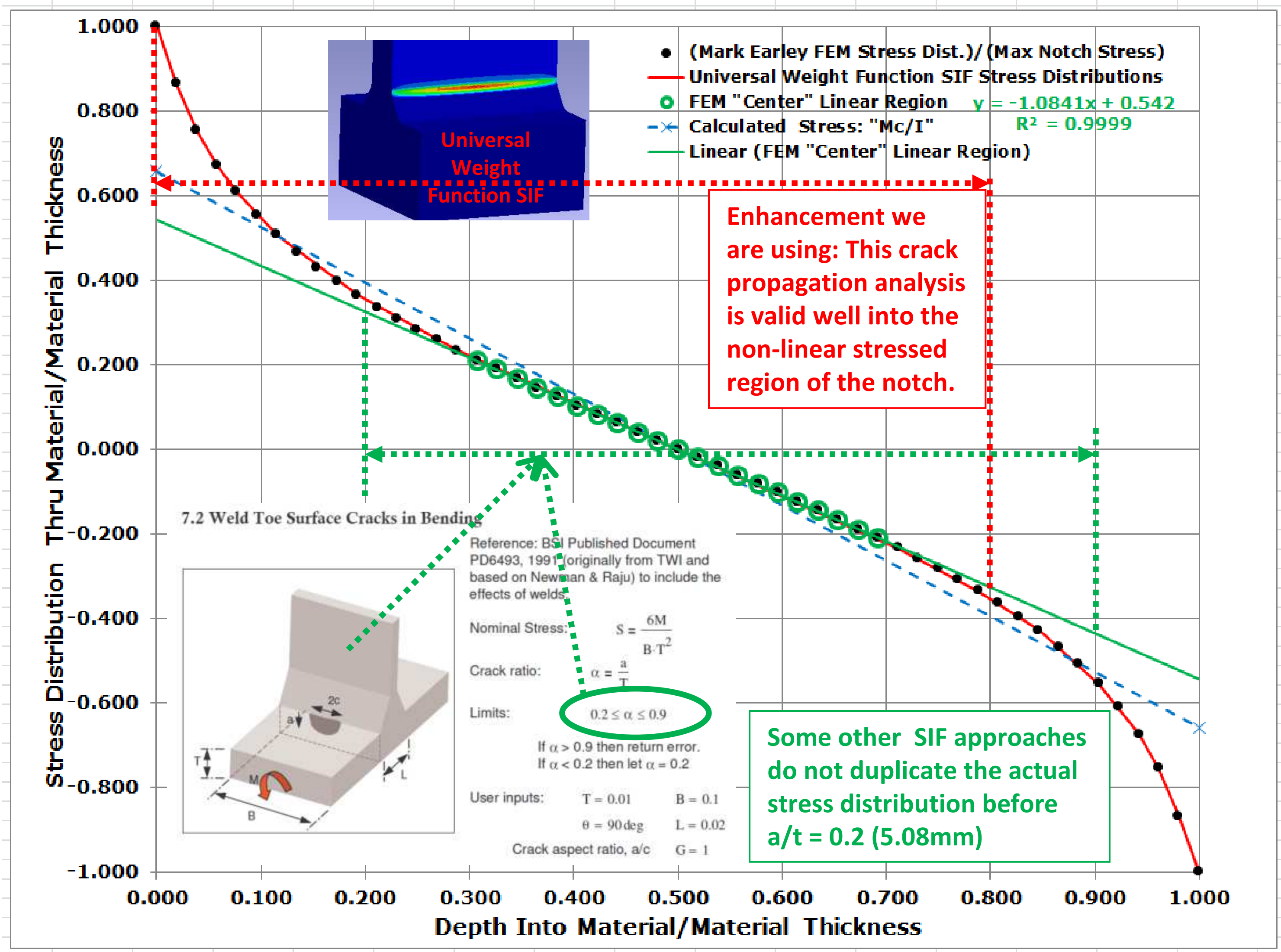


Total Fatigue Life – Summary of Enhancement Used in the Crack Propagation Analysis

Added a Cycle by Cycle Crack Residual Stress Distribution Tracking Capability (CRSDT)
(Calculate, From the Material's Cyclic Stress Strain Curve, the Residual Stress Field of the Crack Tip as it Proceeds through the Time History)

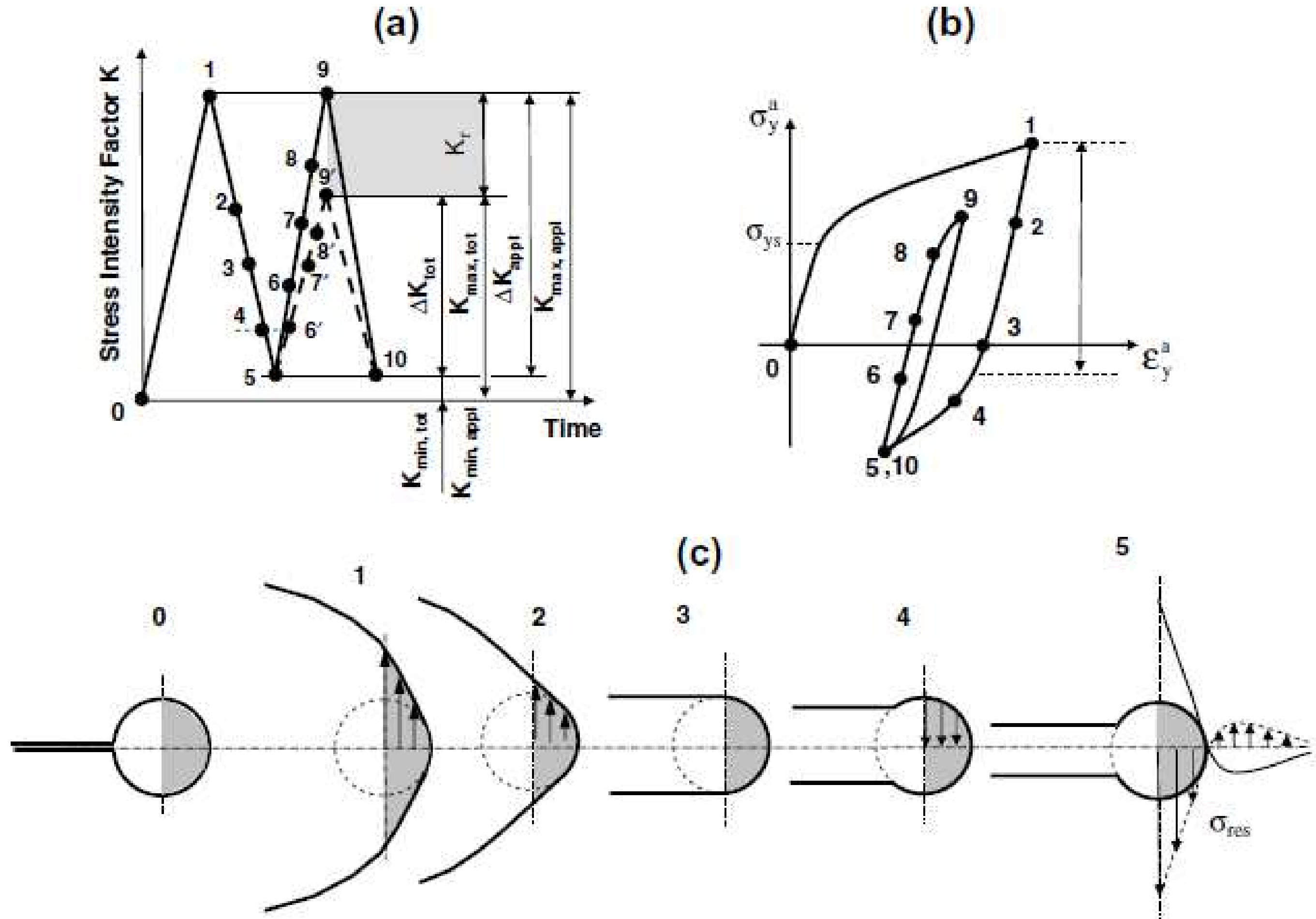
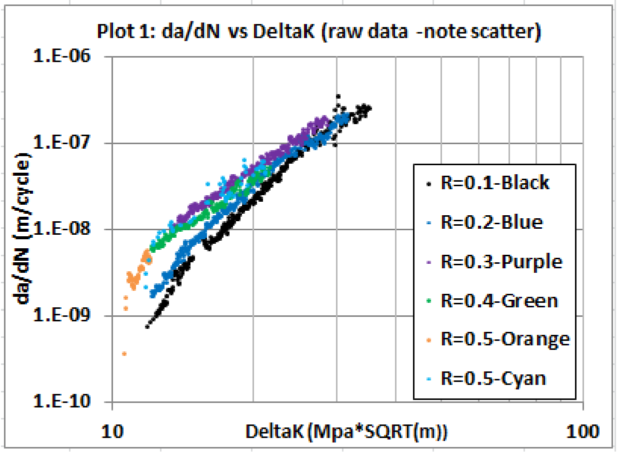
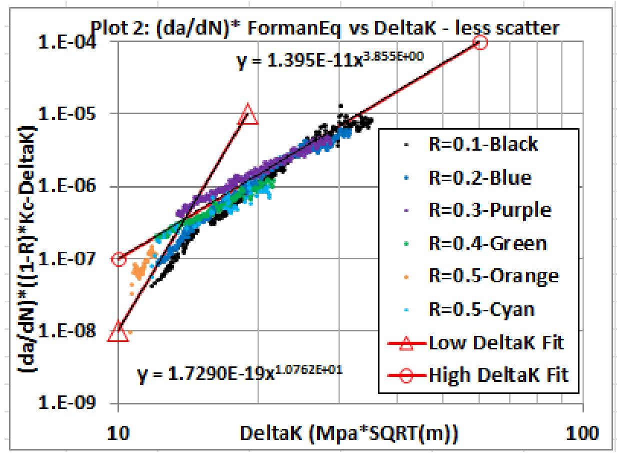


Fig. 1. Schematic crack tip geometry and displacement field, cyclic plastic zone, crack tip stress–strain response and the residual stress distribution: (a) applied load (stress intensity factor) history, (b) qualitative stress–strain response at crack tip, and (c) evolution of the crack opening displacements in the crack tip region.

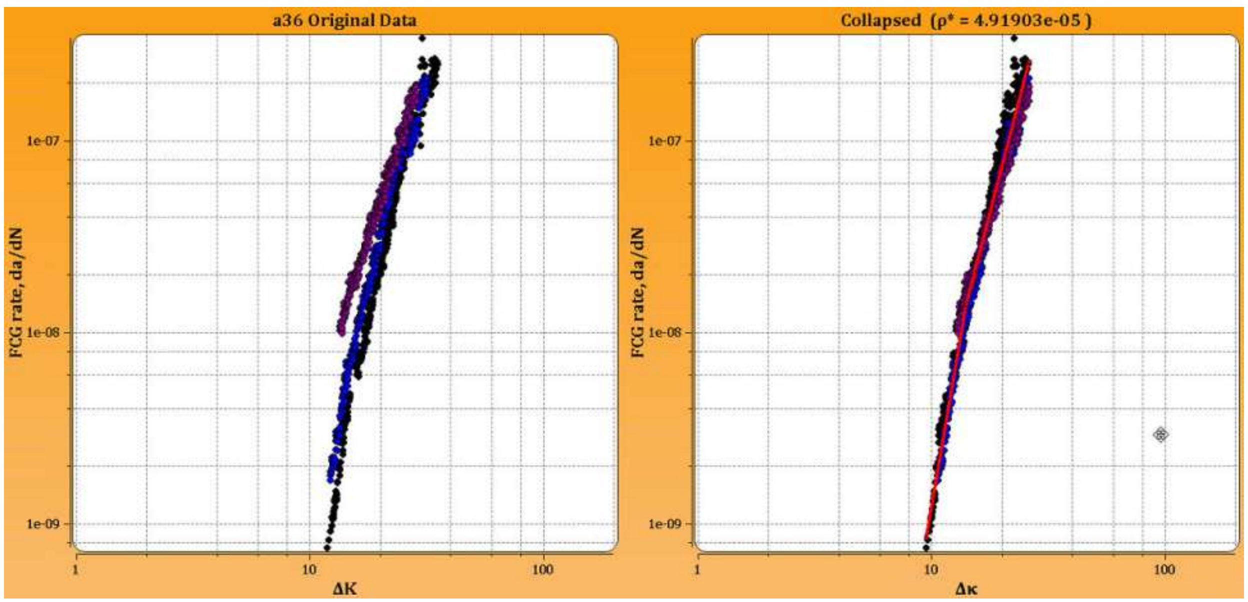
Total Fatigue Life – Summary of Enhancement Used in the Crack Propagation Analysis

Adding a FCG da/dN versus “DeltaKappa”(Driving Force) Material Property (Fitted Data) Curve that is Consistent with the Crack Tip Residual Stress Distribution Tracking Physics/Mathematics. All That is Needed to Obtain the Constants Defining the Curve is Conventional Constant Amplitude da/dN Versus DeltaK Data for at Least Two R Ratios and the Material’s Cyclic Stress Strain Curve.



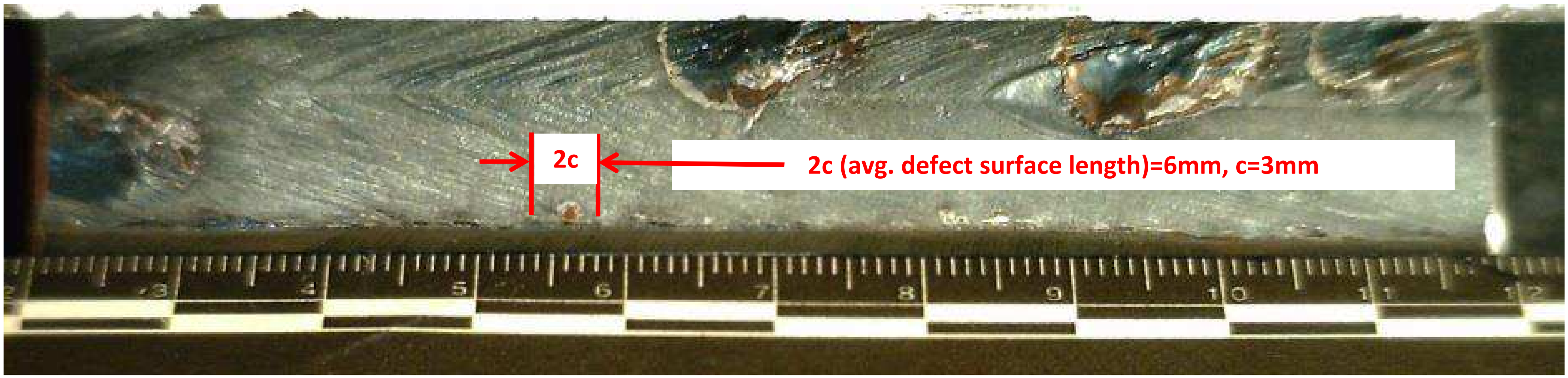


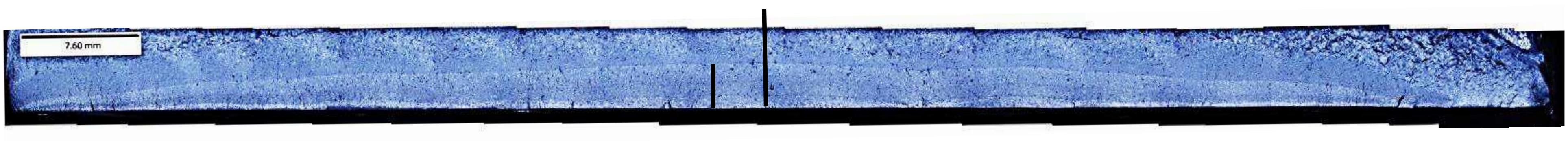
Some material property fitting/modeling approaches have difficulty collapsing the different R Ratio data. Thus there is inherent scatter around the equation used for the actual component life prediction.



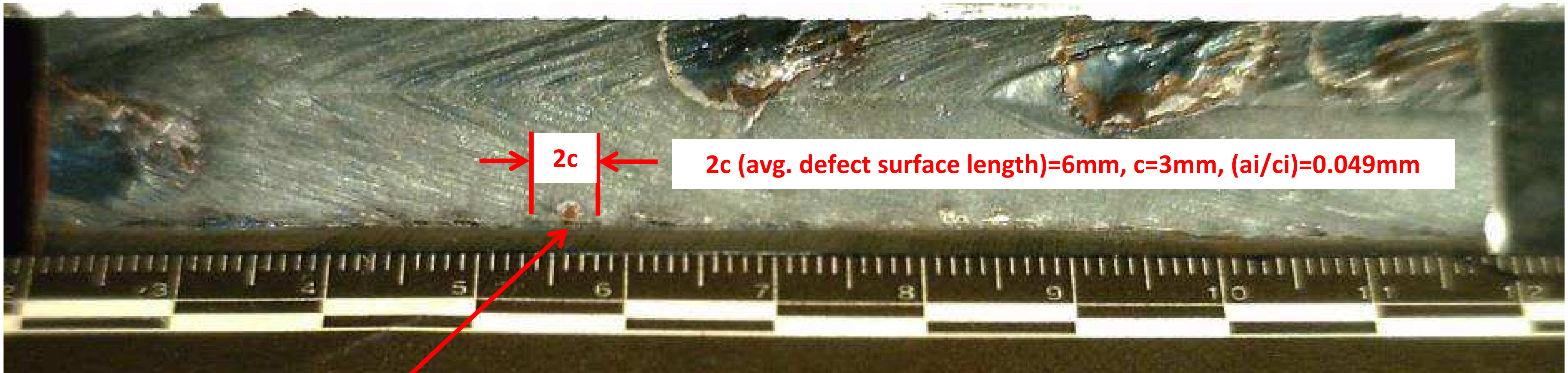
Enhancement we used: There was a minimal amount of scatter around the fit of the raw material property data.

Crack Propagation Analysis Inputs – Define Low Cycle Fatigue “Nucleated” Crack Size and Shape

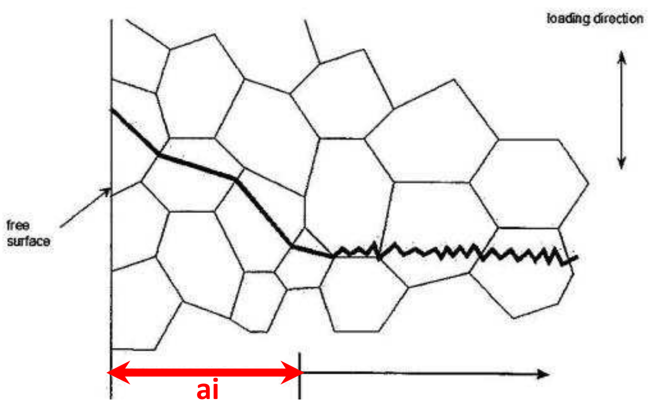




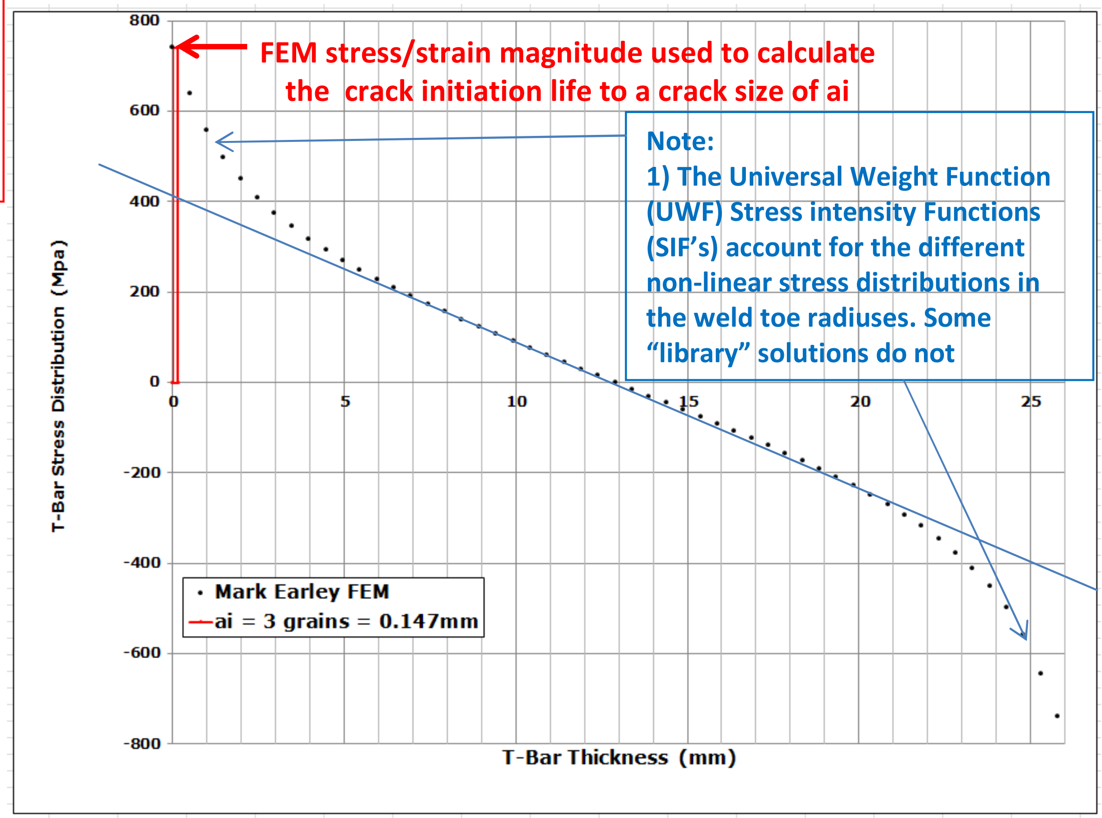
Observations:
1) The crack does not nucleate as a 2 to 1 semi-elliptical surface crack.
2) The crack does not nucleate as a full width edge crack.
3) There appear to be multiple cracks “linking up”
4) The crack aspect ratio changes continuously as the crack propagates through the thickness



Observation:
1) The weld notch root “defects” had some minimal depth prior to crack initiation cycling. Did the crack initiation cycling “sharpen and properly orientate” the defects (prior to linking with other defects?).



Initiated crack depth into the material assumed to be approximately three 0.049mm grain diameters =.147mm

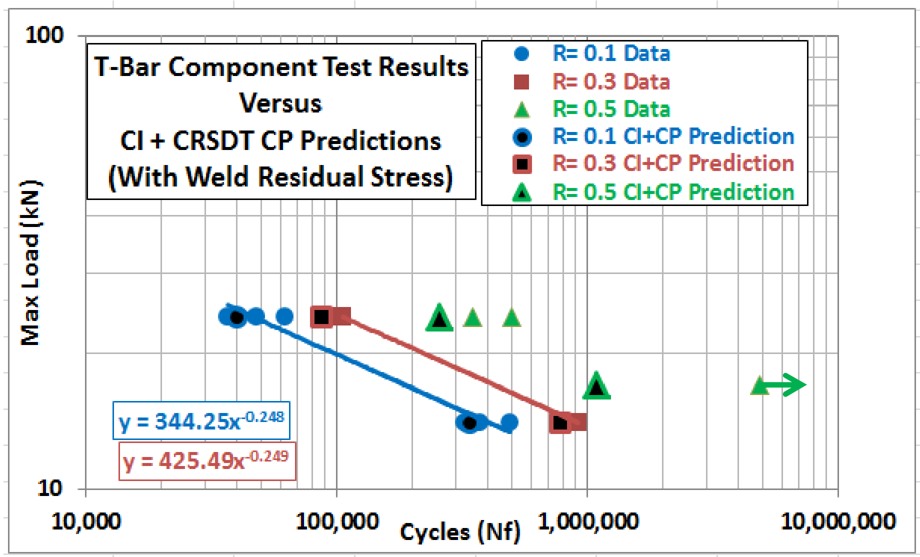


Crack Propagation

The crack propagation segment of the fatigue lives were calculated from the information just provided

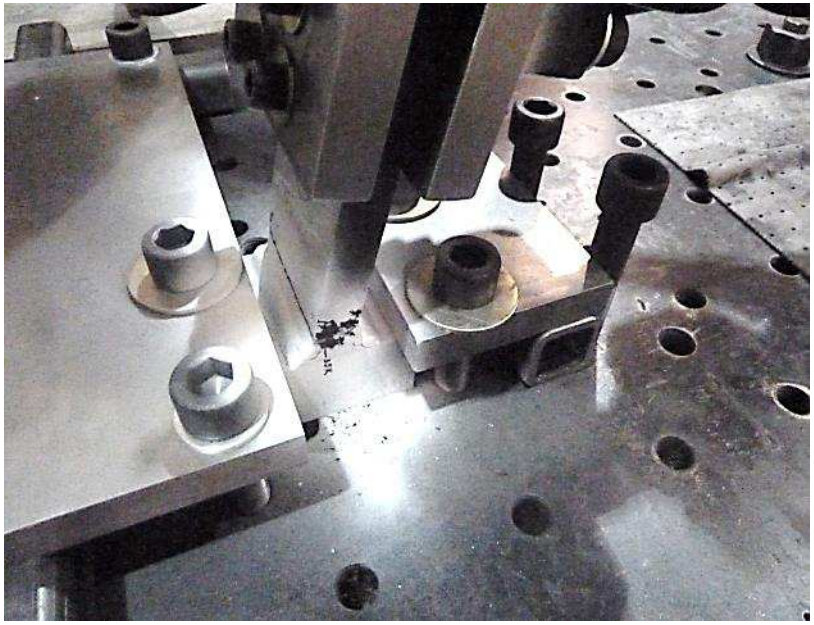
Max Ld kN	R Ratio	Test Cycle	Test Counter Cycles	Weld Sample: Run-Position
24	0.1	Constant Amplitude	36,895	Hand Weld
24	0.1	Constant Amplitude	48,160	2-2
24	0.1	Constant Amplitude	62,047	6-3
24	0.3	Constant Amplitude	105,522	4-2
24	0.5	Constant Amplitude	262,628	4-3
24	0.5	Constant Amplitude	349,002	6-4
24	0.5	Constant Amplitude	503,441	5-?
14	0.1	Constant Amplitude	325,579	5-3
14	0.1	Constant Amplitude	375,813	3-4
14	0.1	Constant Amplitude	494,456	3-3
14	0.3	Constant Amplitude	922,658	3-1
17	0.5	Constant Amplitude	4,900,000 NC*	5-1
24	0.1/0.5	Block Loading	138,421	4-1

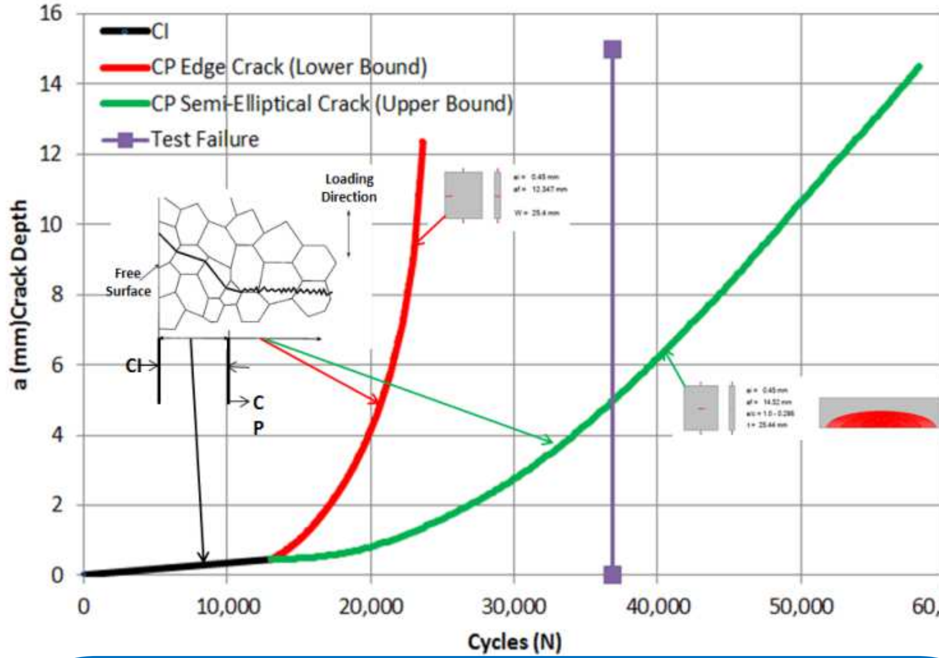
*Note: No crack growth observed visually

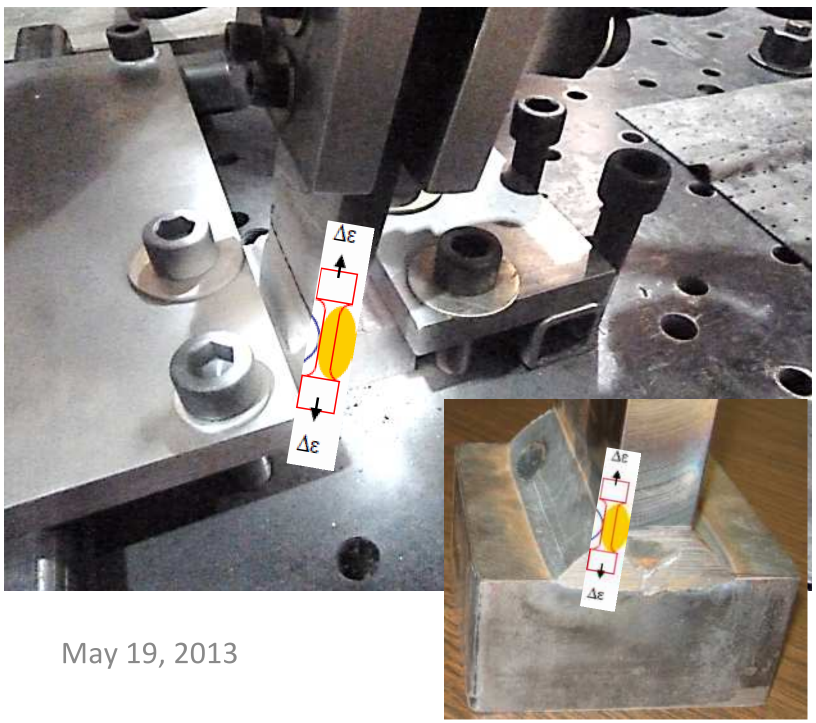


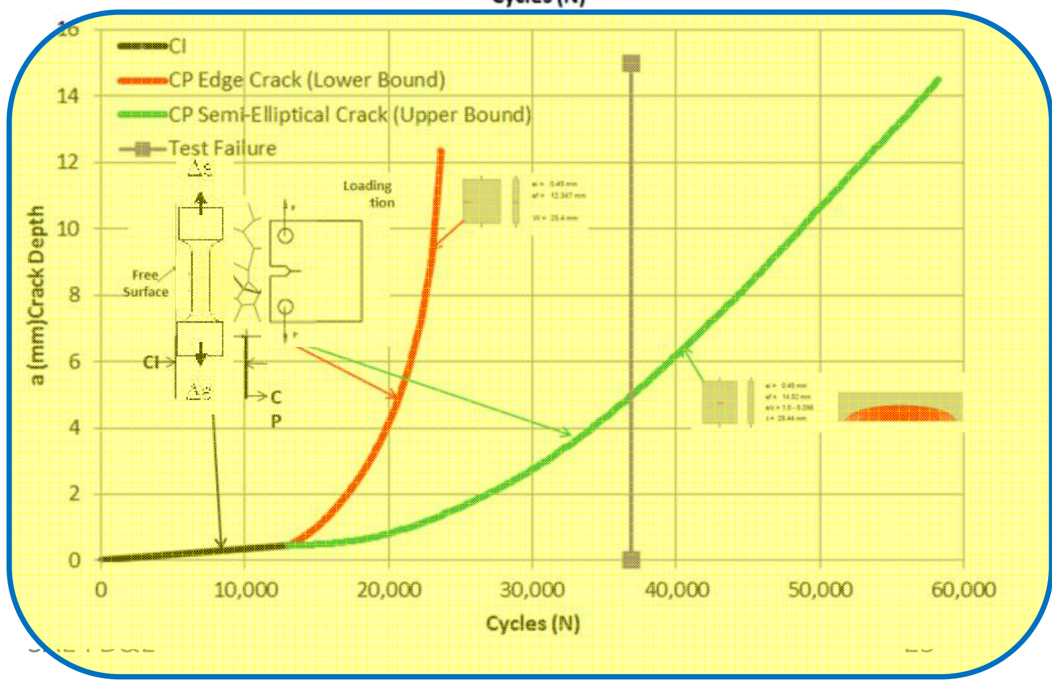
RF

Total Fatigue Life – Third: Calculate Crack Initiation + Crack Propagation Life

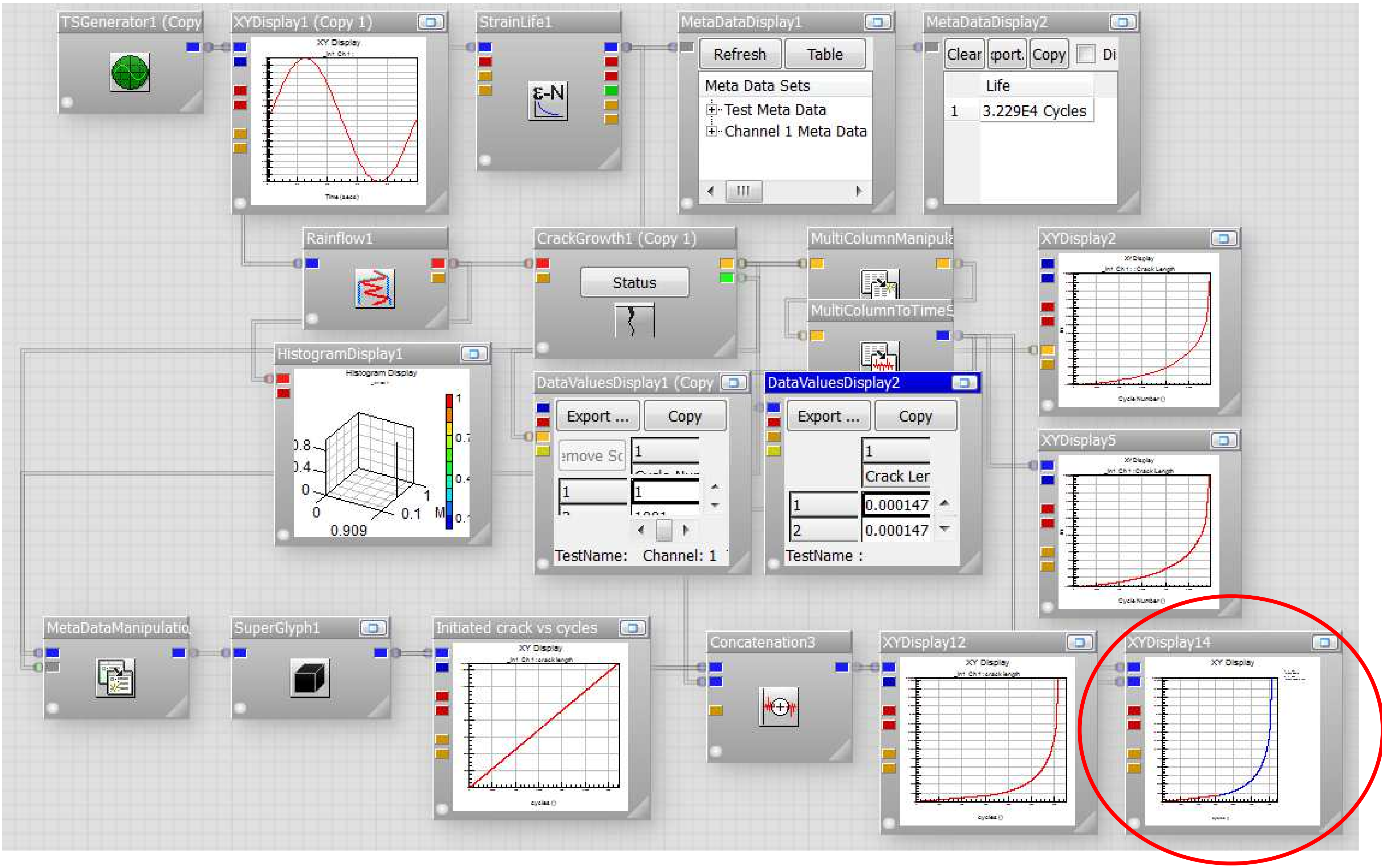




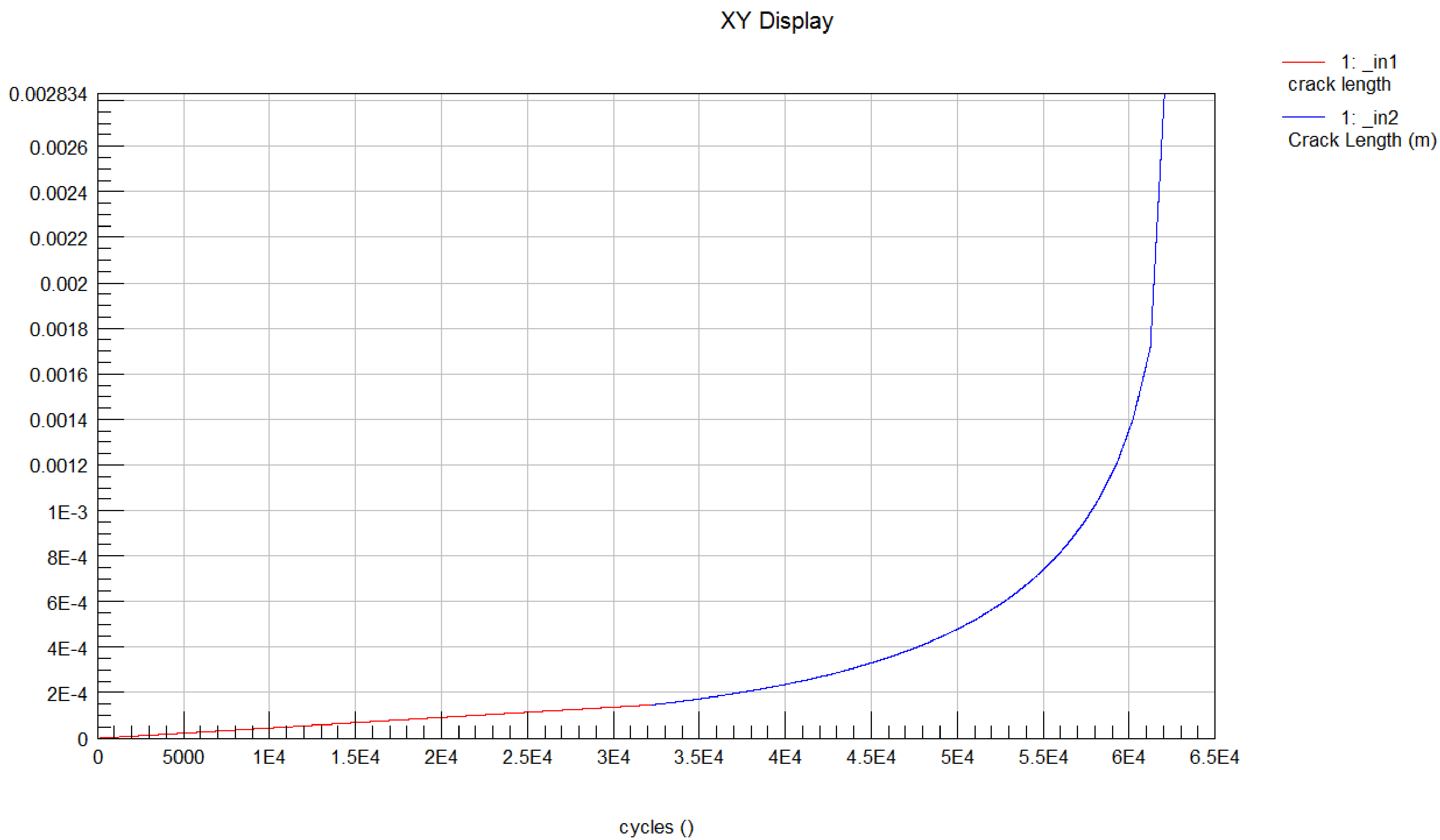




Total Fatigue Life -Just Add the Previous Crack Initiation & Crack Propagation Analysis Together

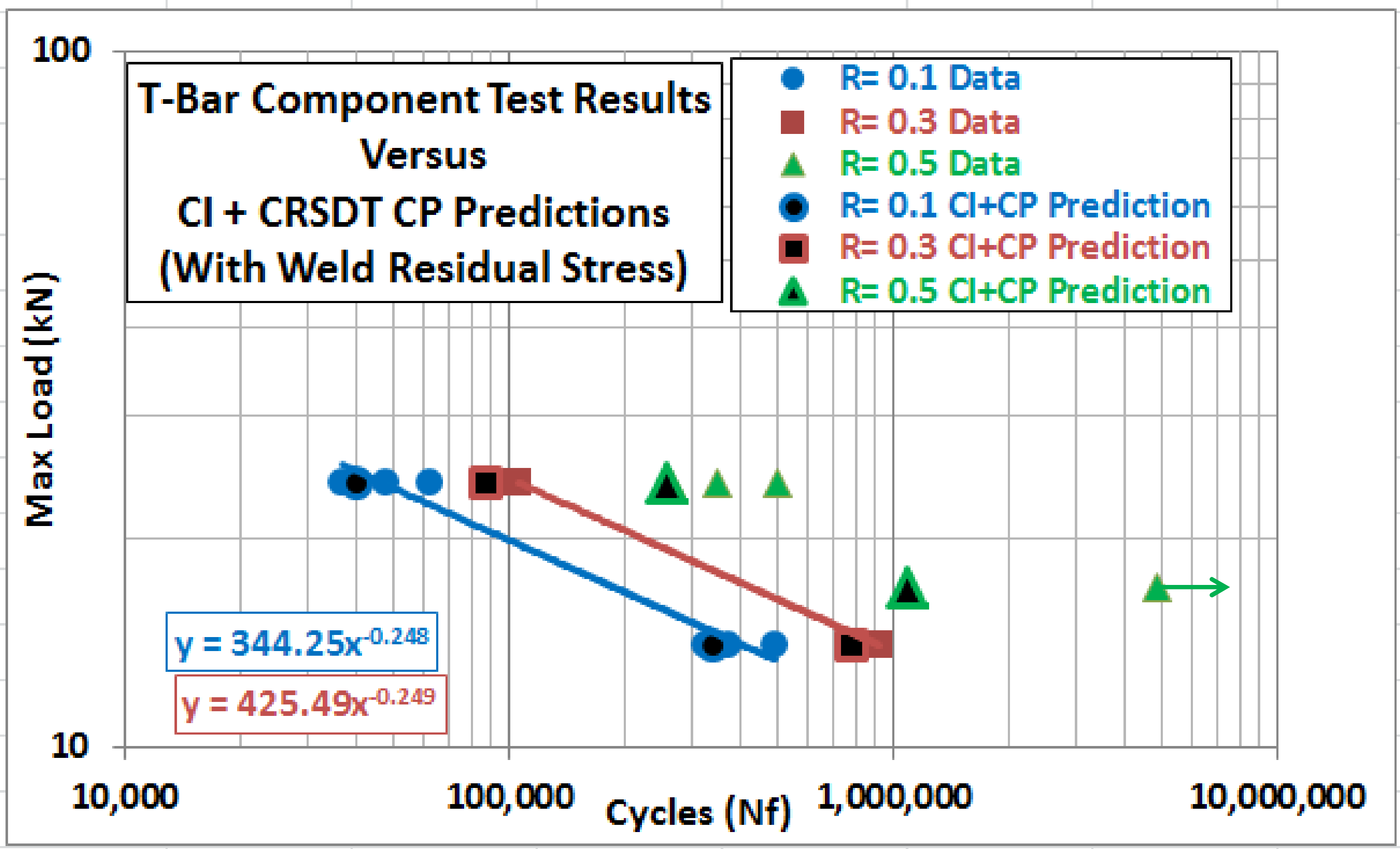


Total Fatigue Life-Just Add the Previous Crack Initiation & Crack Propagation Analysis Together



Total Fatigue Life: Crack Initiation + Crack Propagation Analysis

The total fatigue lives were calculated as just indicated



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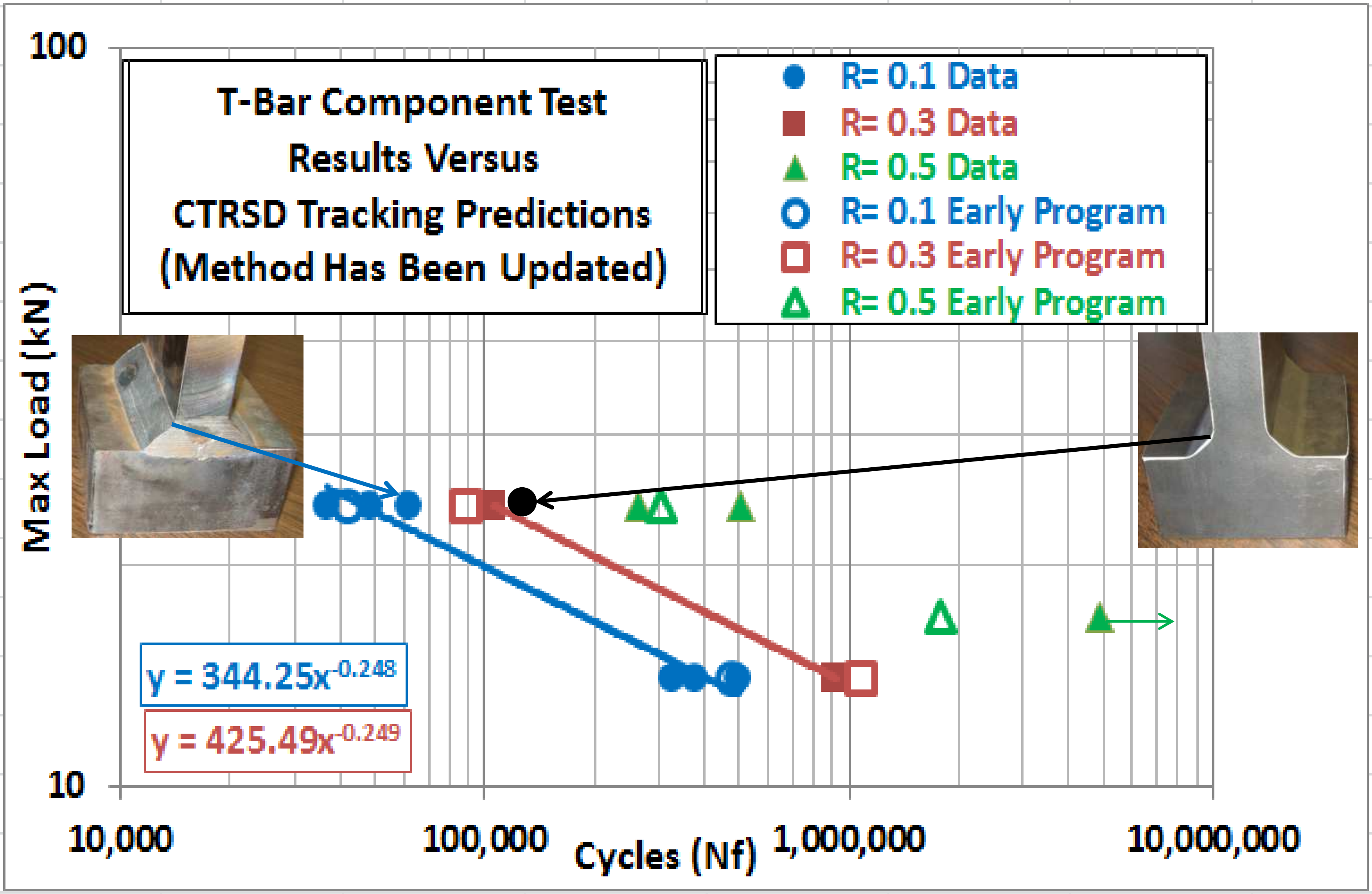
Total Fatigue Life: Crack Initiation+ Crack Propagation Analysis – Machined Sample – Backup Slide

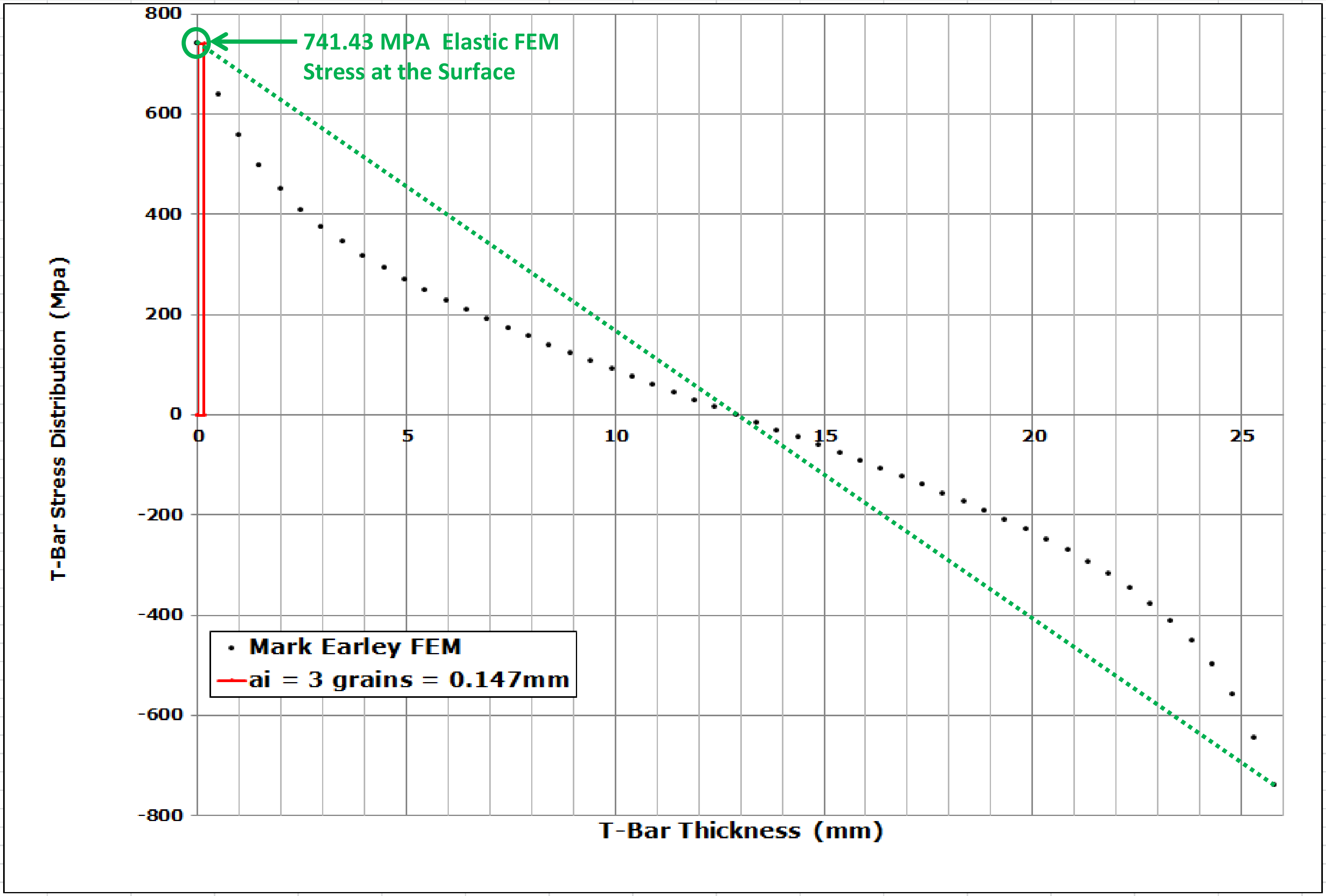


RF

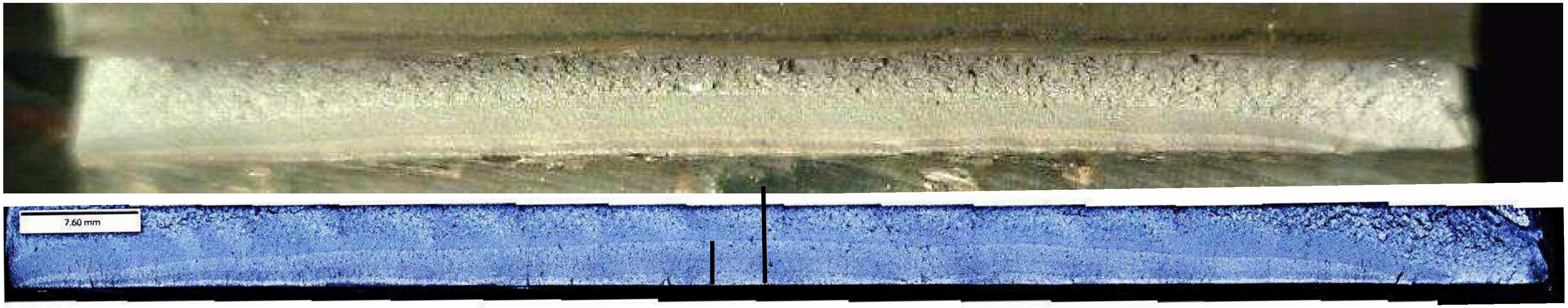
Thank You

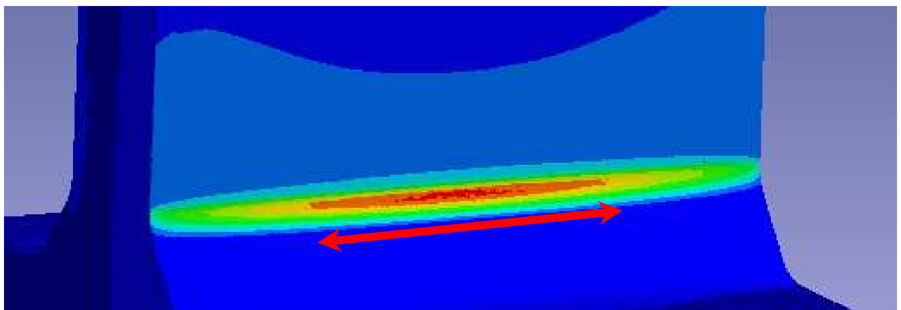
Backup Slides

Total Fatigue Life: Crack Initiation + Crack Propagation Analysis - Backup Slide

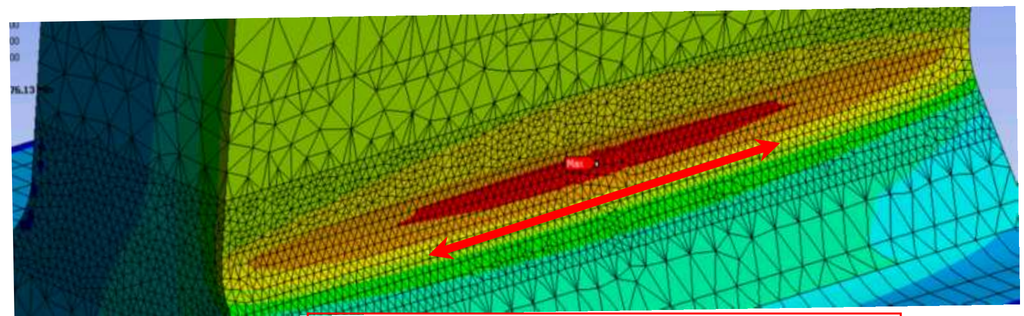


Crack Propagation Analysis Inputs – Define Low Cycle Fatigue "Nucleated" Crack Size and Shape





Fatigue Damage From GlyphWorks Design Life



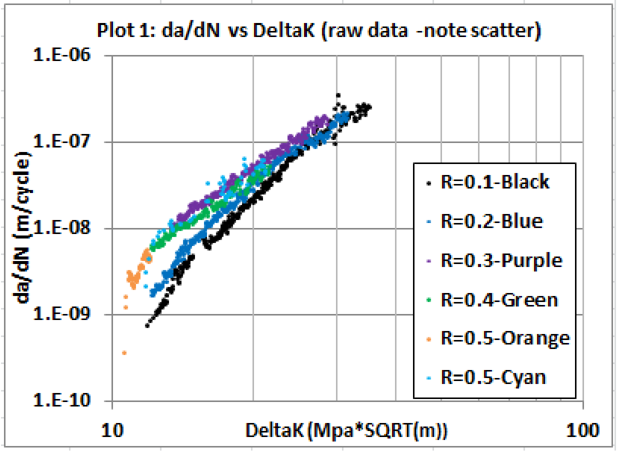
Principal Stress From Mark Earley's FEM

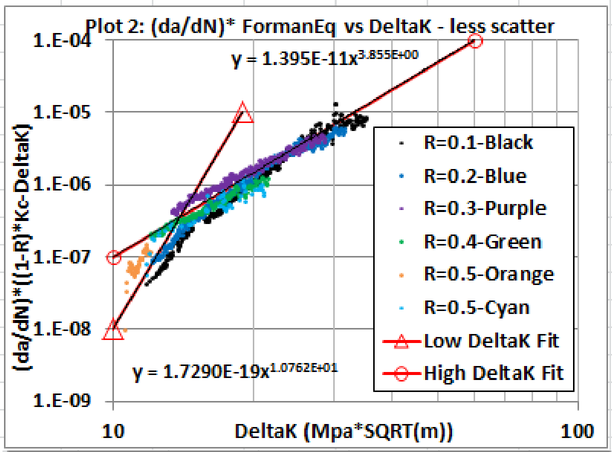
2c

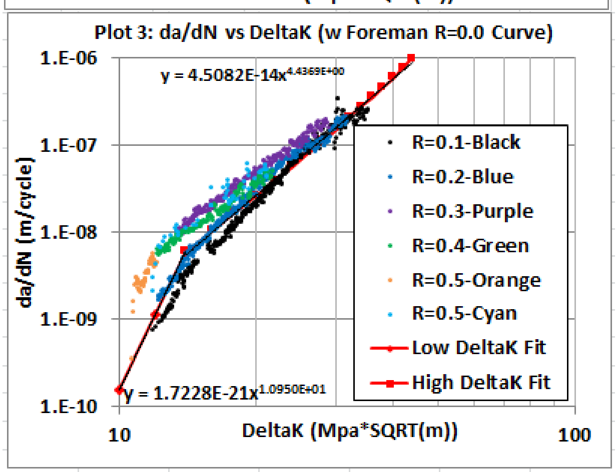
Shortest lived, most high stressed "potentially initiated crack length" on the surface is approximately one half the specimen width: 2c = 50.8mm. Therefore c = 25.4 mm. The initial crack aspect ratio is assumed to be <u>a/c = .147/25.4 = .005765</u>

Observations:
1) The crack does not nucleate as a 2 to 1 semi-elliptical surface crack.
2) The crack does not nucleate as a full width edge crack.
3) There appear to be multiple cracks "linking up"
4) The crack aspect ratio changes <u>continuously</u> as the crack propagates through the thickness

Crack Propagation Analysis - Crack Growth Material Properties - Current Method







Used	In This
GlyphWorks	Analysis
da/dN	DeltaK
m/cycle	Mpa*SQRT(m)
5.0000	7.7617E-14
13.7689	5.0955E-09
75.0000	9.4072E-06
A Kc from one of the crack propagation tests was: 75 Mpa*SQRT(m)	

Plot 1:
A review of the da/dN vs DeltaK raw data reveals that, at least, a bi-linear fit of the data is required and the different R Ratio data needs to be collapsed to one curve or applied individually.

Plot 2:
The “Interpolated Foreman” is the only bi-linear fit of the data currently available in GlyphWorks and it does a “fair” job of collapsing the different R Ratio data toward one curve.

Note: This set of data, from one consistent heat of steel, should “collapse tighter” then this. When one selects a set of “fit constants” off (say) the internet, what is it’s data scatter?

Plot 3:
So the “Interpolated Foreman” will be used for this analysis. For reference the R=0.0 curve (used by GlyphWorks as its reference curve) is shown here overlayed on the pre-collapsed data.