Predicting Total Fatigue Life
(Crack Initiation and Crack Propagation)

Presented to the SAE FD&E Committee
at Minneapolis, MN on 22 October 2013
(Prepared by Semyon Mikheevskiy and Tom Cordes

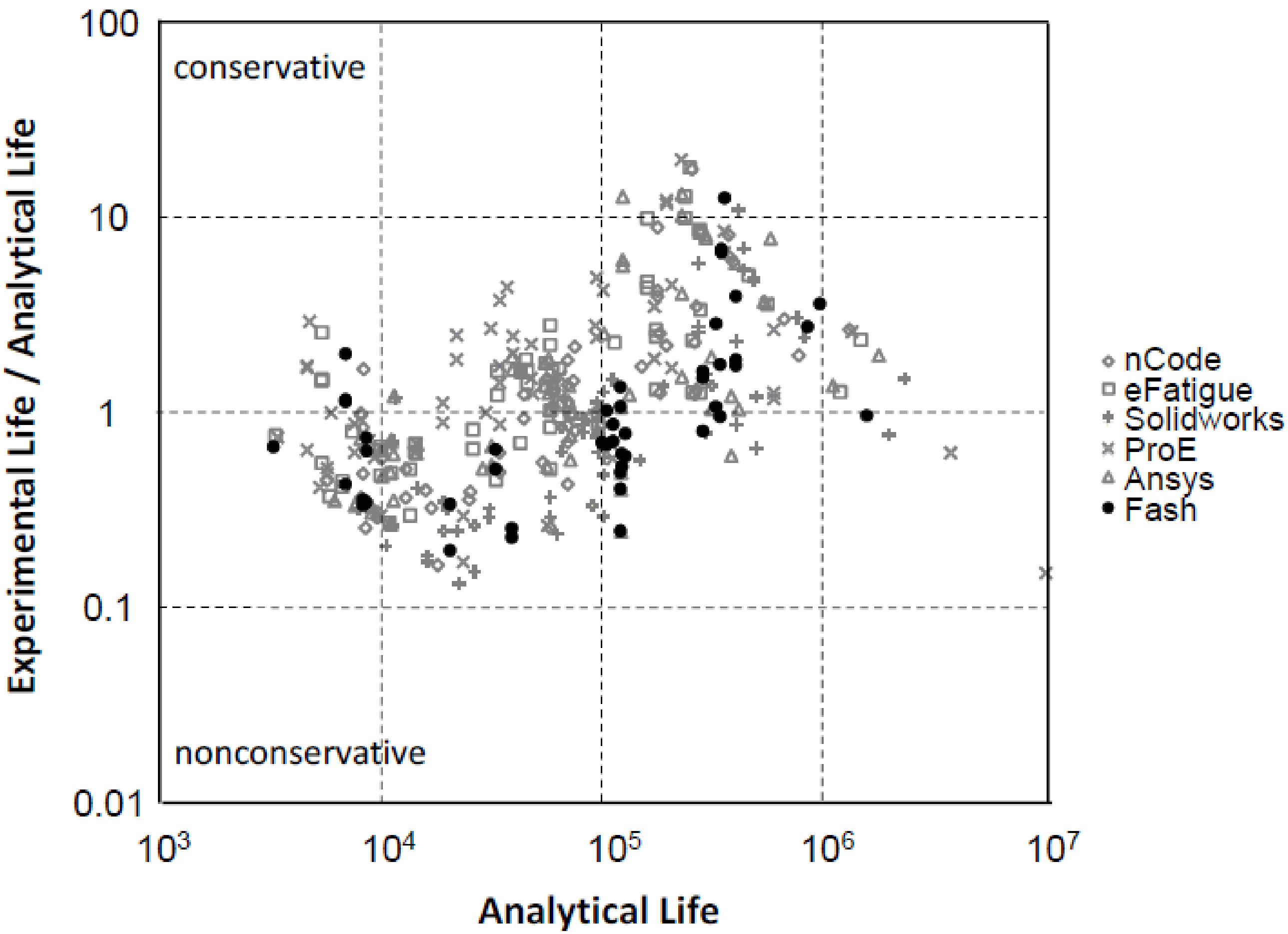
→ 1. **Overview of Effort**

2. **Residual Stress Distribution Concerns/Questions**

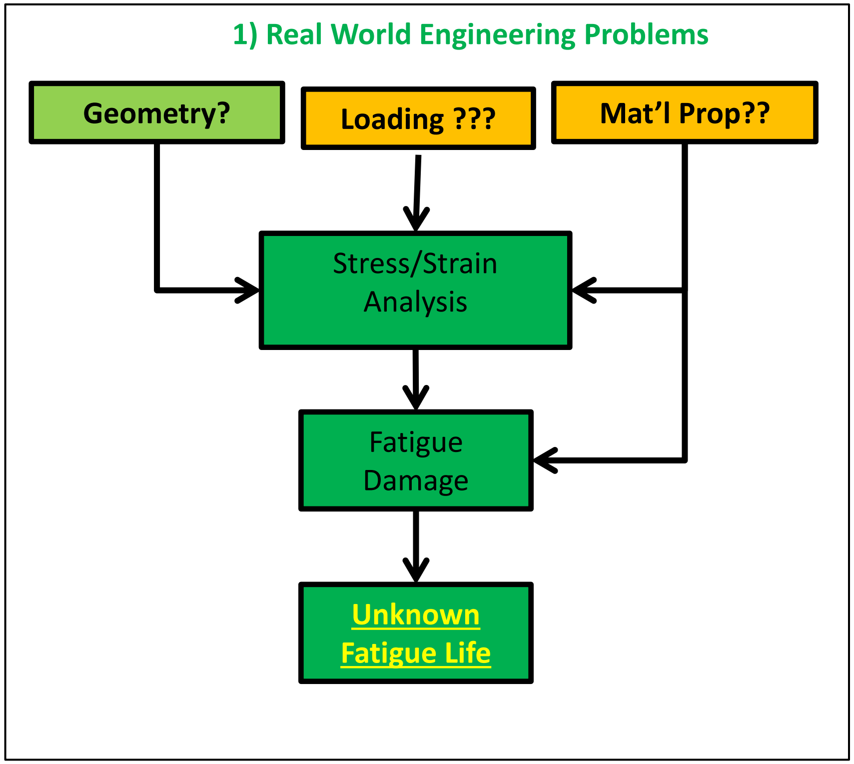
3. **Crack Initiation and Crack Propagation Analysis Background?**

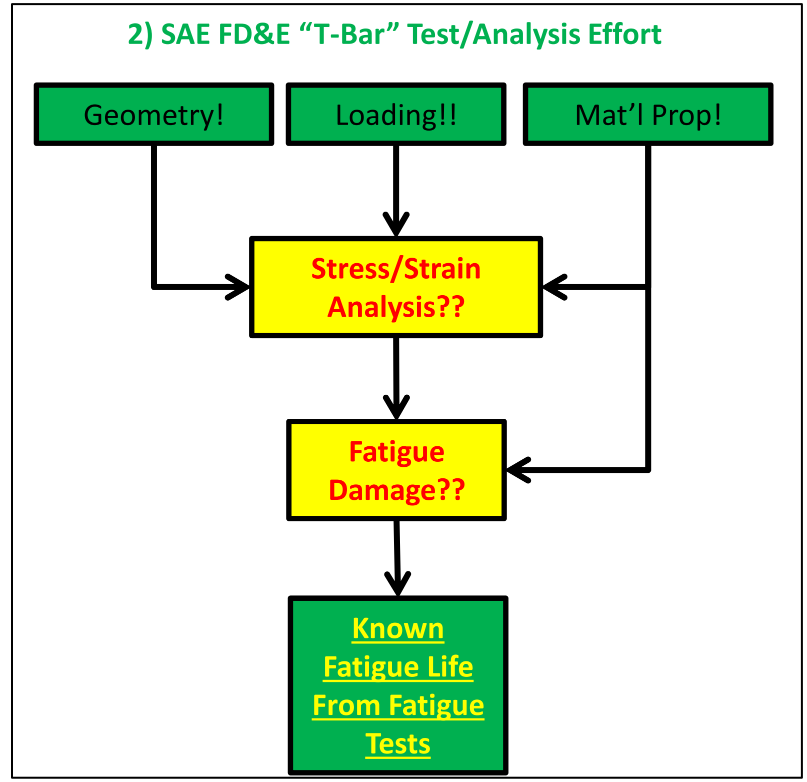
Previous SAE FD&E Analysis to Test Correlation Effort Results

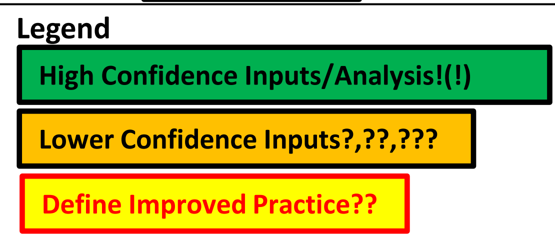
A brief summary of the fatigue theories and strategies employed by the various software packages used to compute fatigue lives is given below. A common feature of all of the analysis is that they used what may be termed the strain-life method. Commonality ends there. They all used different notch rules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



Total Fatigue Life: Crack Initiation and Crack Propagation





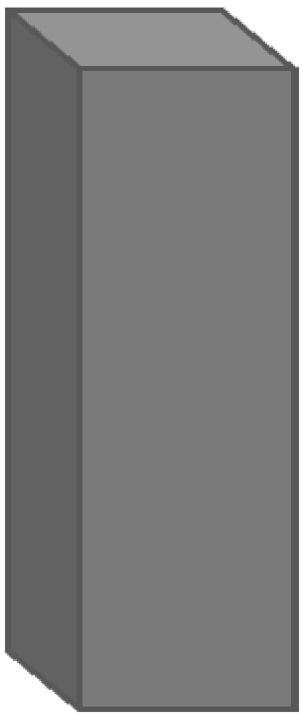


This effort is using "very well defined/controlled analysis inputs" to address an engineering problem to validate (or not) a potential "Total Fatigue Life Prediction Improved Practice"

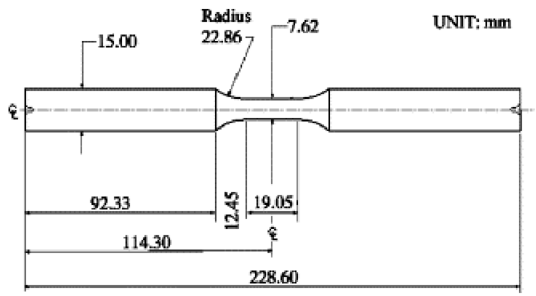
Total Fatigue Life: Crack Initiation and Crack Propagation Analysis

Maintain Exact – Same Steel Pedigree (Material Characterization) Definition/Documentation

Purchased "Enough" 4 A36 20ft HR bars



Microstructure, Chemistry & Hardness Sample



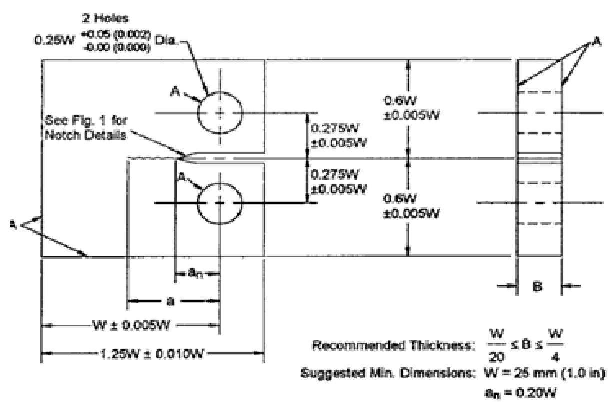
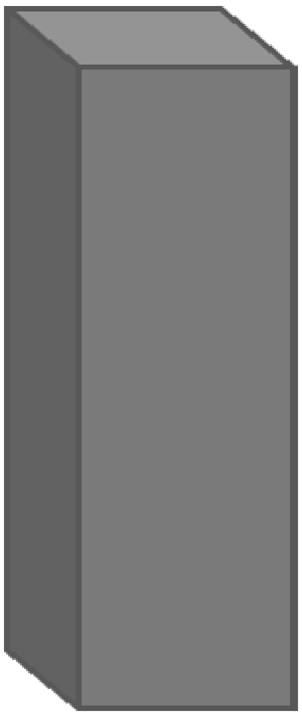
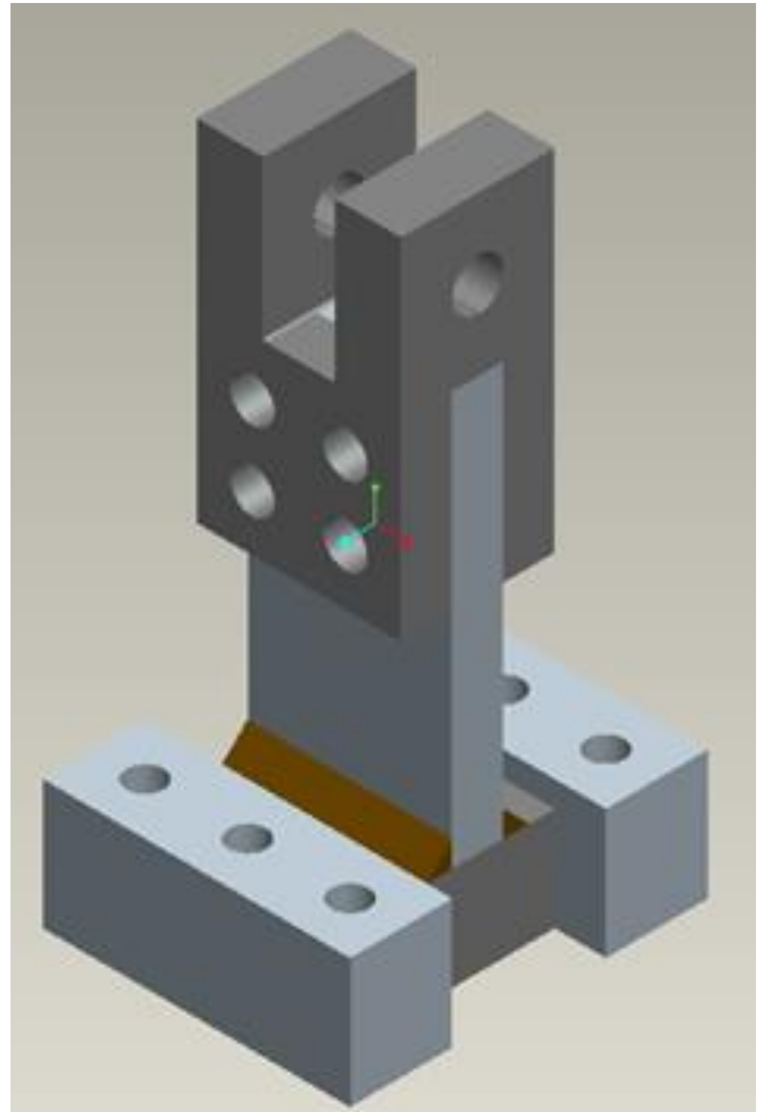


FIG. A1.1 Standard Compact-Tension C(T) Specimen for Fatigue Crack Growth Rate Testing
W=76.2 mm (3 in), B= 19.05 mm (0.75 in)

Total Fatigue Life: Crack Initiation and Crack Propagation Analysis

Load Carrying Weld
Specimen Configuration and Test Fixture/FEM Boundary Conditions



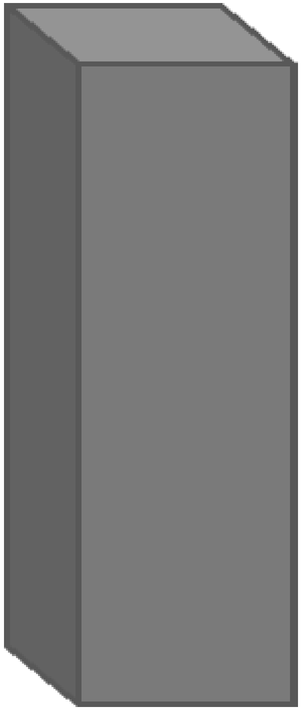


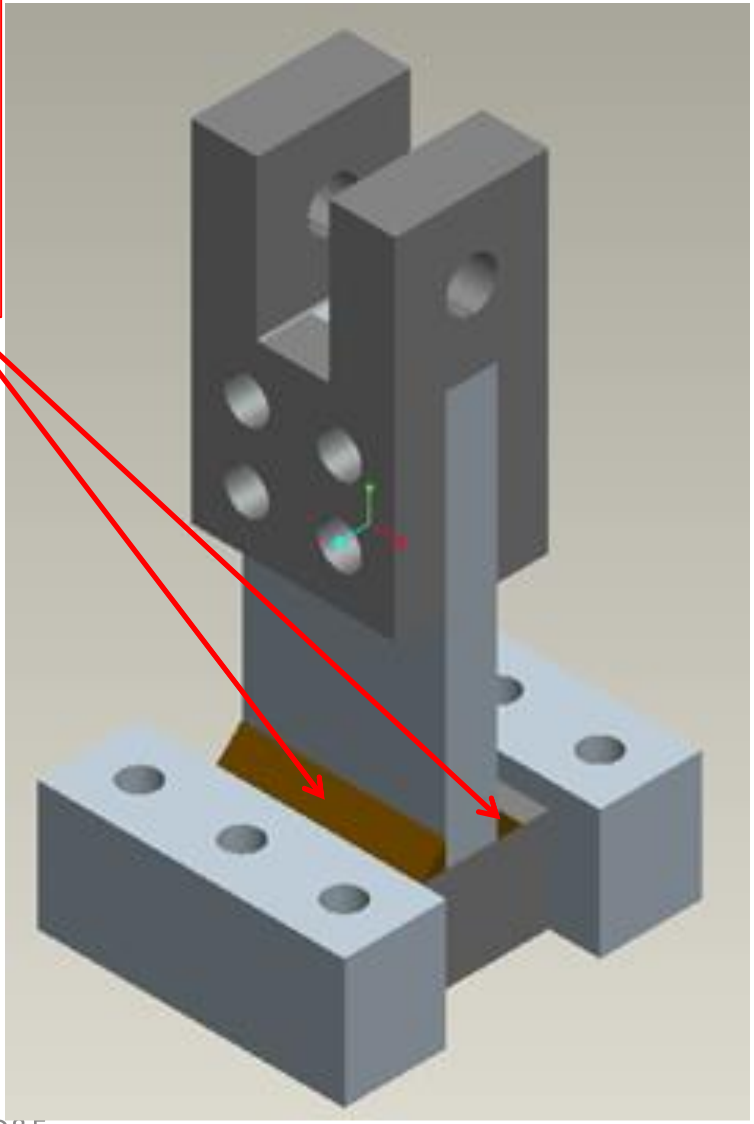
See Next Slide

Machined

Specimen Configuration and Test Fixture/FEM Boundary Conditions

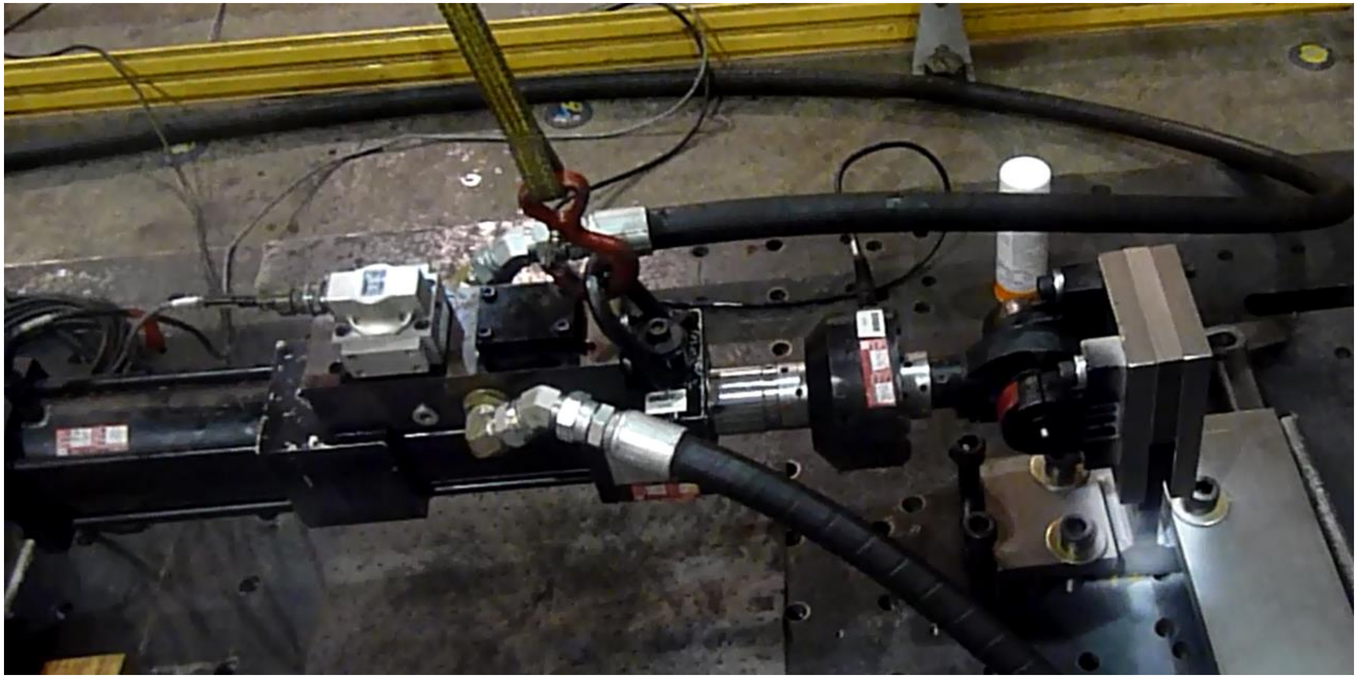
Eliminate the weld entirely – machine the entire specimen from the 101.6 mm x 101.6 mm bar. Duplicate, by machining, the weld profile and weld toe radius as closely as possible so the sample is consistently made from the same material. Comparing the test results from these samples relative to the test results from the previously welded samples. This will confirm (or not) how sound an assumption it is to use the base material properties when analyzing welded structures.

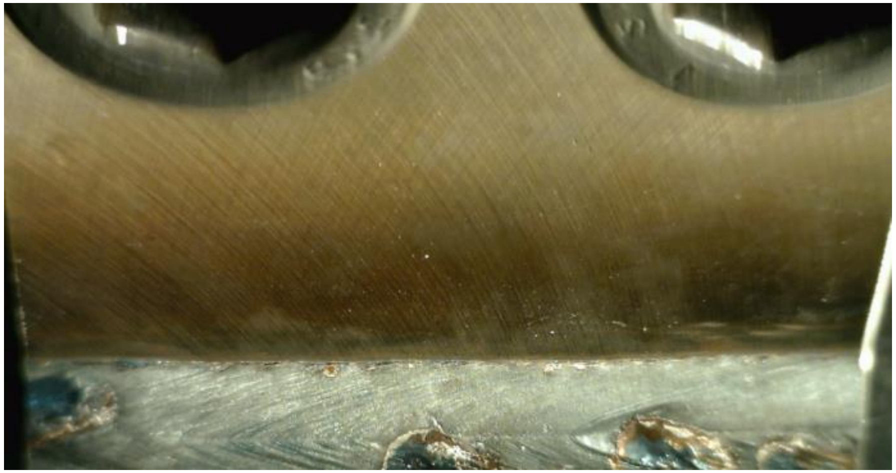




Total Fatigue Life: Crack Initiation and Crack Propagation Analysis

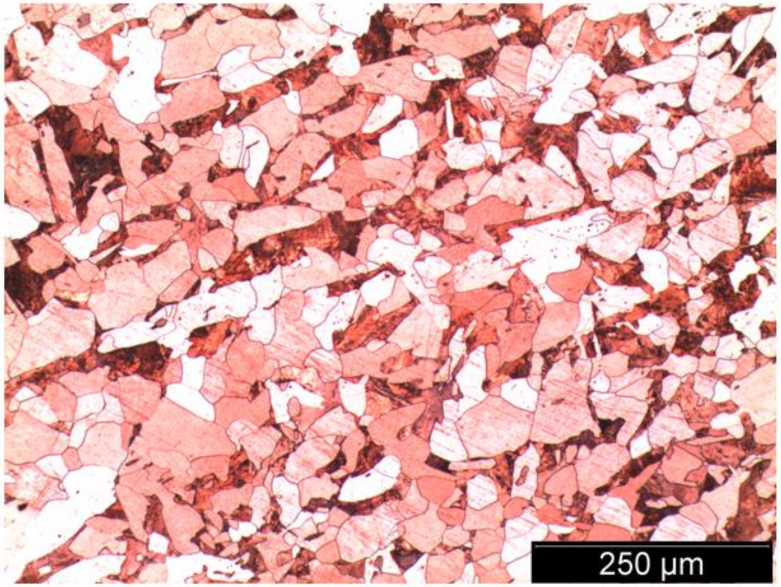
Play Three Video's:





Steel Microstructure, Hardness, Grain Size and Chemistry

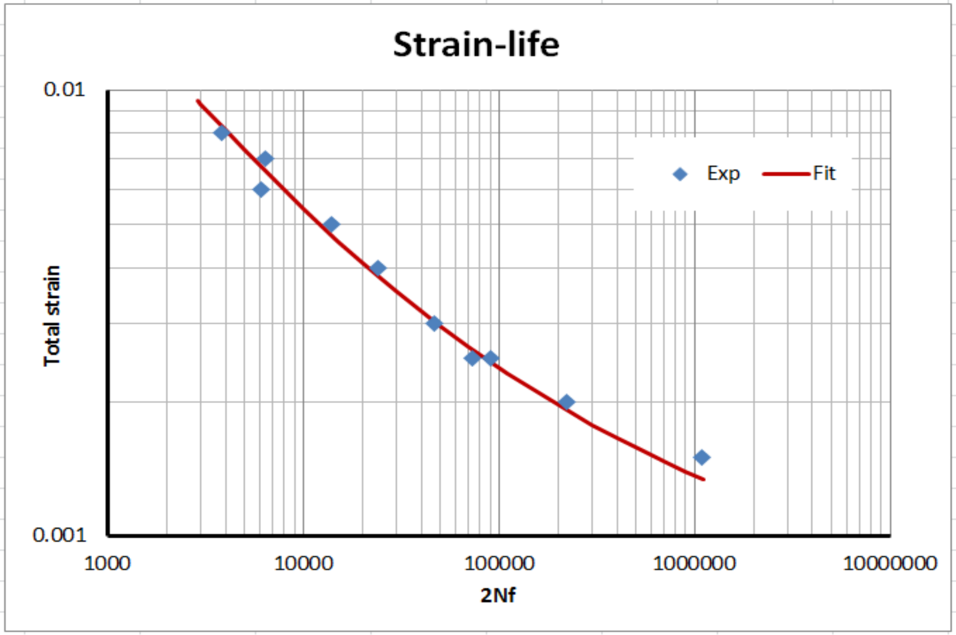
- Longitudinal Section
- Hardness: 79 HRB
- Grain size: 6

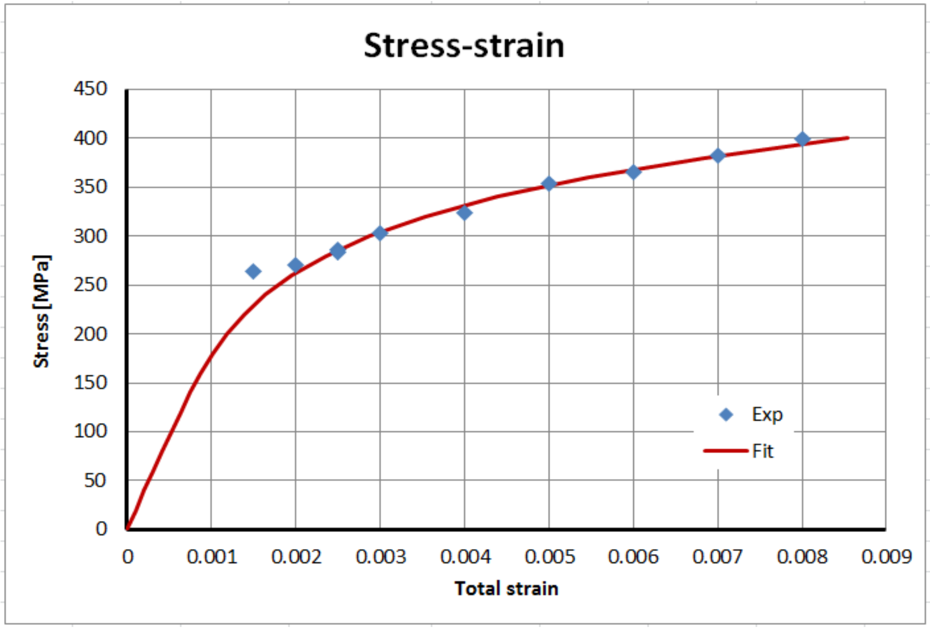


	C165 %	C-LOW %	Mn403.4 %	Si288 %	P177 %	S180 %	Cr_Calc.	Ni341 %	Mo386 %	Cu327 %
Average	0.199	0.212	0.807	0.237	0.012	0.044	0.093	0.100	0.006	0.260
Std. Deviation	0.009	0.0099	0.009	0.003	0.001	0.002	0.000	0.002	0.000	0.004
%RSD	4.60	4.68	1.08	1.17	4.32	5.38	0.48	1.81	5.72	1.45
1 (Yes)	0.189	0.202	0.804	0.236	0.011	0.041	0.093	0.099	0.006	0.257
2 (Yes)	0.188	0.200	0.804	0.240	0.011	0.043	0.093	0.098	0.006	0.255
3 (Yes)	0.187	0.200	0.803	0.238	0.011	0.041	0.092	0.097	0.005	0.256
4 (Yes)	0.198	0.212	0.801	0.239	0.012	0.042	0.093	0.101	0.006	0.260
5 (Yes)	0.199	0.213	0.800	0.237	0.012	0.041	0.093	0.100	0.006	0.258
6 (Yes)	0.201	0.214	0.798	0.239	0.013	0.043	0.092	0.101	0.006	0.260
7 (Yes)	0.208	0.223	0.820	0.233	0.012	0.046	0.093	0.102	0.006	0.266
8 (Yes)	0.208	0.223	0.819	0.236	0.012	0.047	0.093	0.102	0.006	0.264
9 (Yes)	0.210	0.225	0.817	0.232	0.012	0.046	0.093	0.102	0.006	0.263

	V411 %	Al396 %	Ti337 %	Nb316 %	Co340 %	W400 %	Pb220 %	Fe249 %	B208 %
Average	0.000	0.002	0.00	0.00	0.00	0.00	0.012	98.2	0.001
Std. Deviation	0.000	0.000	0.00	0.00	0.00	0.00	0.001	0.020	0.000
%RSD	263.23	10.12	0.00	0.00	0.00	0.00	10.66	0.02	11.48
1 (Yes)	0.00	0.002	0.00	0.00	0.00	0.00	0.012	98.2	0.001
2 (Yes)	0.00	0.002	0.00	0.00	0.00	0.00	0.013	98.3	0.001
3 (Yes)	0.00	0.002	0.00	0.00	0.00	0.00	0.013	98.3	0.001
4 (Yes)	0.000	0.002	0.00	0.00	0.00	0.00	0.010	98.2	0.001
5 (Yes)	0.00	0.002	0.00	0.00	0.00	0.00	0.011	98.2	0.001
6 (Yes)	0.000	0.002	0.00	0.00	0.00	0.00	0.012	98.2	0.001
7 (Yes)	0.00	0.002	0.00	0.00	0.00	0.00	0.011	98.2	0.001
8 (Yes)	0.00	0.002	0.00	0.00	0.00	0.00	0.013	98.2	0.001
9 (Yes)	0.00	0.002	0.00	0.00	0.00	0.00	0.014	98.2	0.000

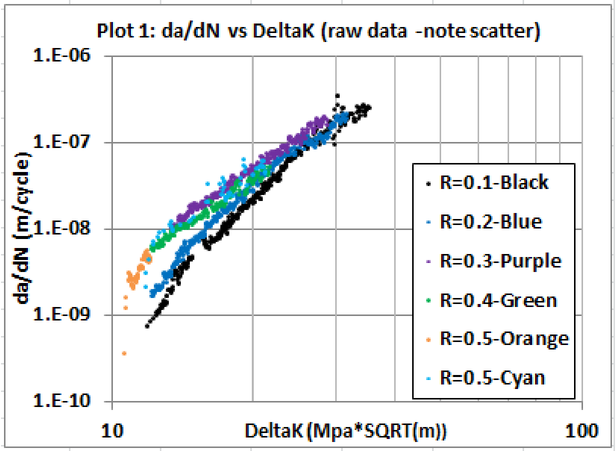
Steel Crack Initiation Strain-Life and Cyclic Stress-Strain Curves and "Fit" Analysis Constants

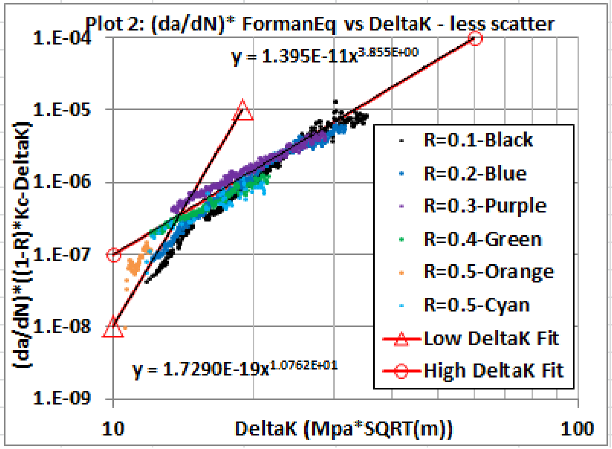


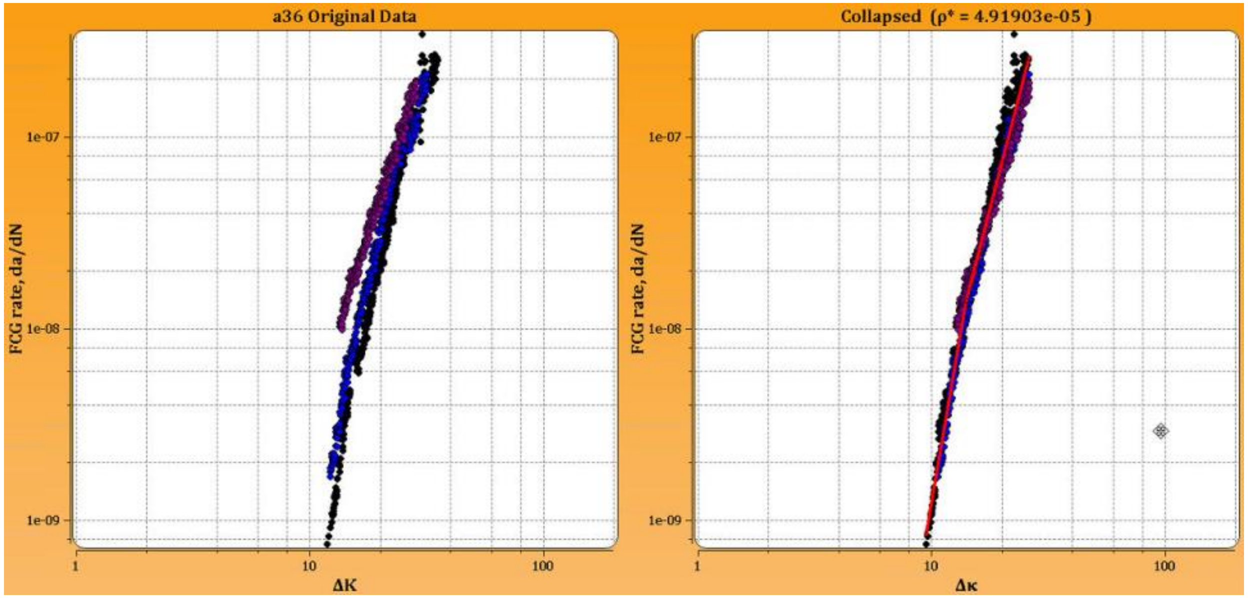


E	Sys	K'	n'	sf'	ef'	b	c
190786	324.12	991.4	0.1799	1025.9	0.7627	-0.1132	-0.5837

Steel Crack Propagation da/dN vs DeltaK Raw Data Plots and "Fit" Constants





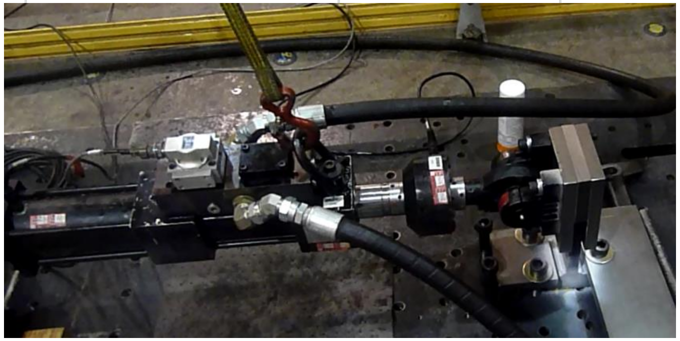


Some material property fitting/modeling approaches have difficulty collapsing the different R Ratio data. Thus there is inherent scatter around the equation used for the actual component life prediction.

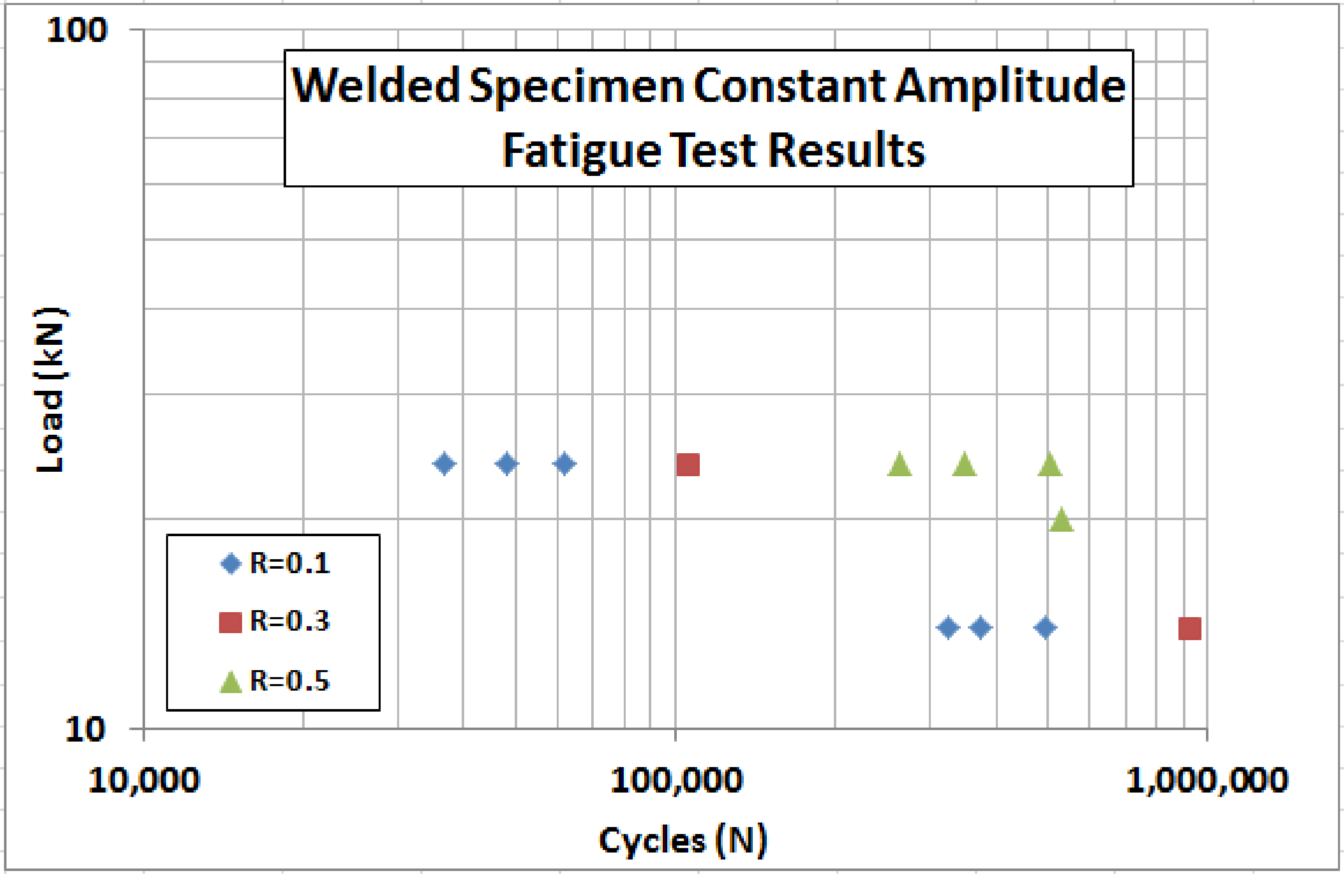
Welded Specimen Constant Amplitude Fatigue Test Results

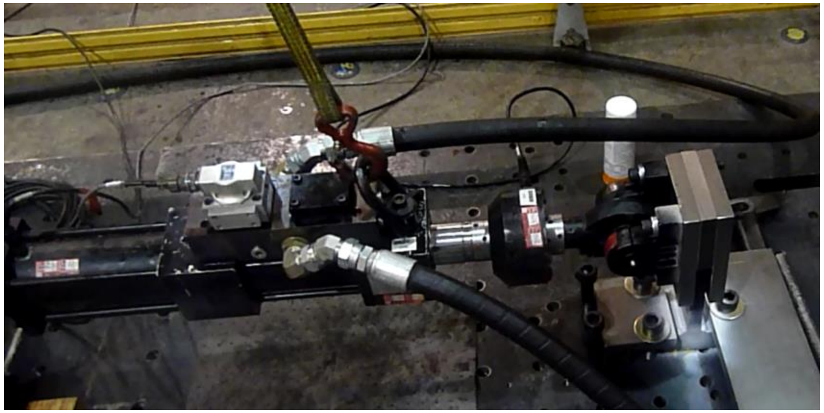
With time histories and videos of all tests

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-?
20	0.5	Constant Amplitude	529,250	4-4?
17	0.5	Constant Amplitude	4,900,000 NC*	5-1
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
24	0.1/0.5	Block Loading	138,421	4-1
*Note (NC): No crack growth found visually or by magnaflow				



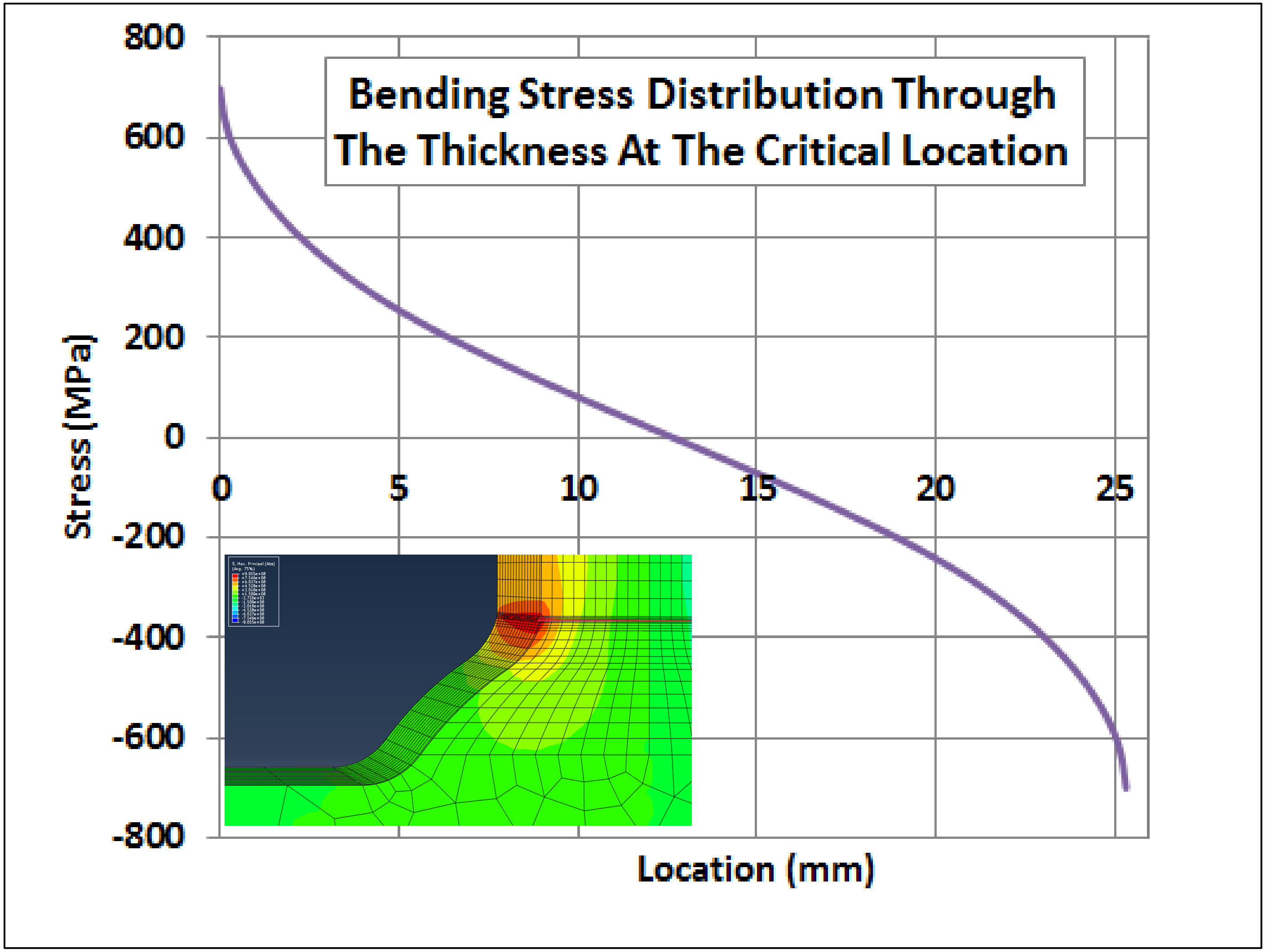
Total Fatigue Life: Crack Initiation and Crack Propagation Analysis





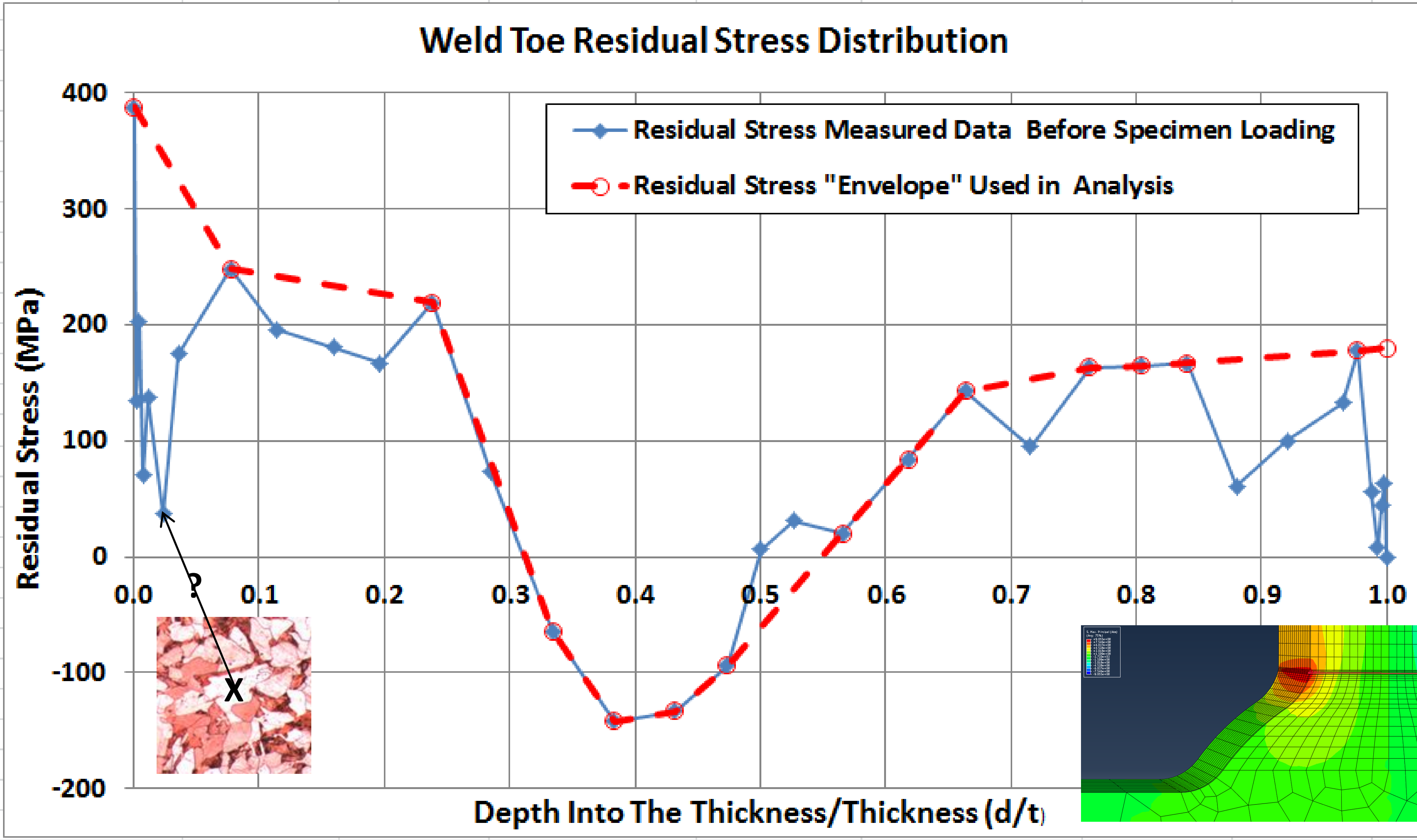
Total Fatigue Life: Crack Initiation and Crack Propagation Analysis

Other analysis/data needed to complete the Total Fatigue Life Analysis:



Total Fatigue Life: Crack Initiation and Crack Propagation Analysis

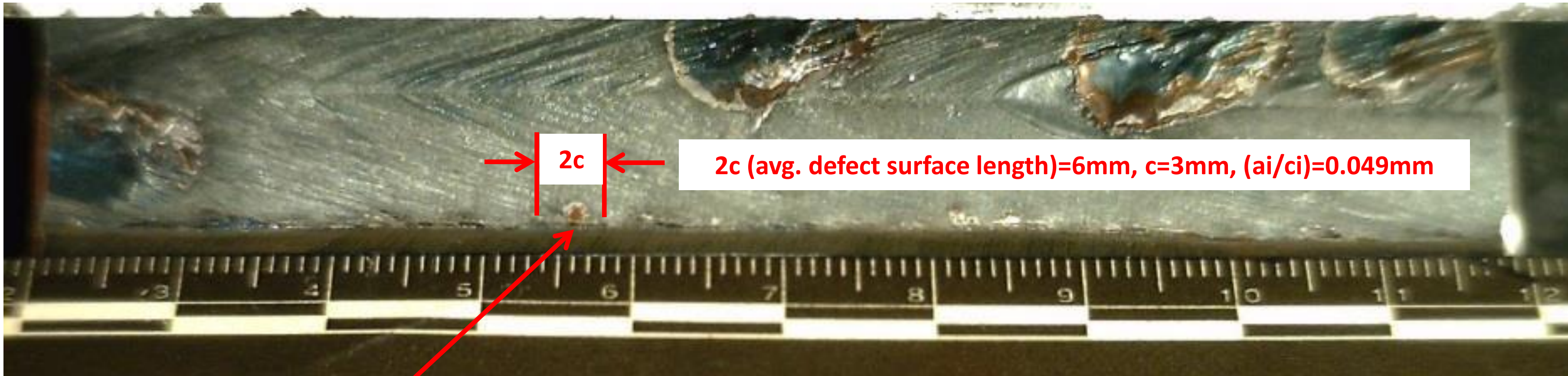
Other analysis/data needed to complete the Total Fatigue Life Analysis:



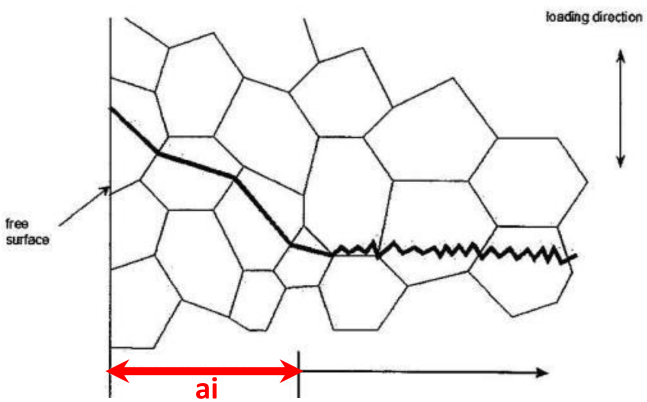
Analysis #1

Tom Cordes
Fatigue Test and Analysis Engineer at HBM-nCode
After failing at retirement from John Deere (at JD for 24 years)

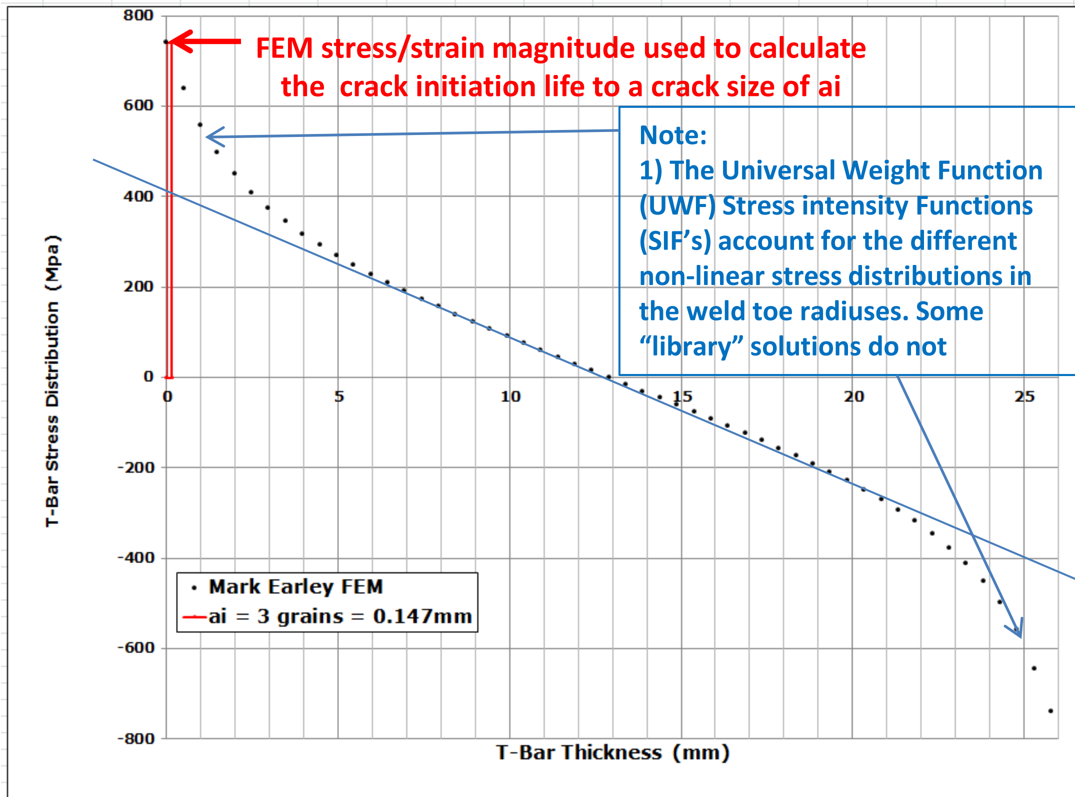
Crack Propagation Analysis Inputs – Define Low Cycle Fatigue “Nucleated” Crack Size and Shape



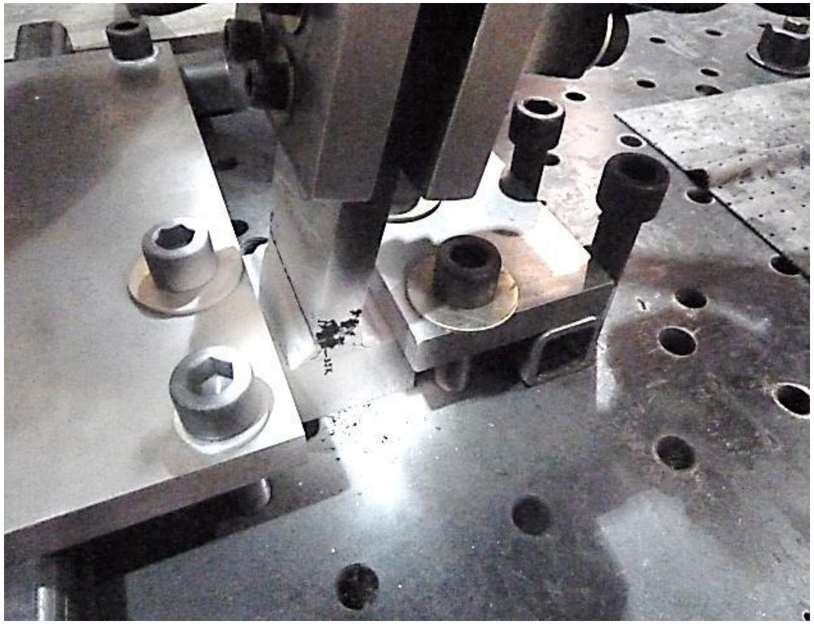
Observation:
1) The weld notch root “defects” had some minimal depth prior to crack initiation cycling. Did the crack initiation cycling “sharpen and properly orientate” the defects (prior to linking with other defects?).

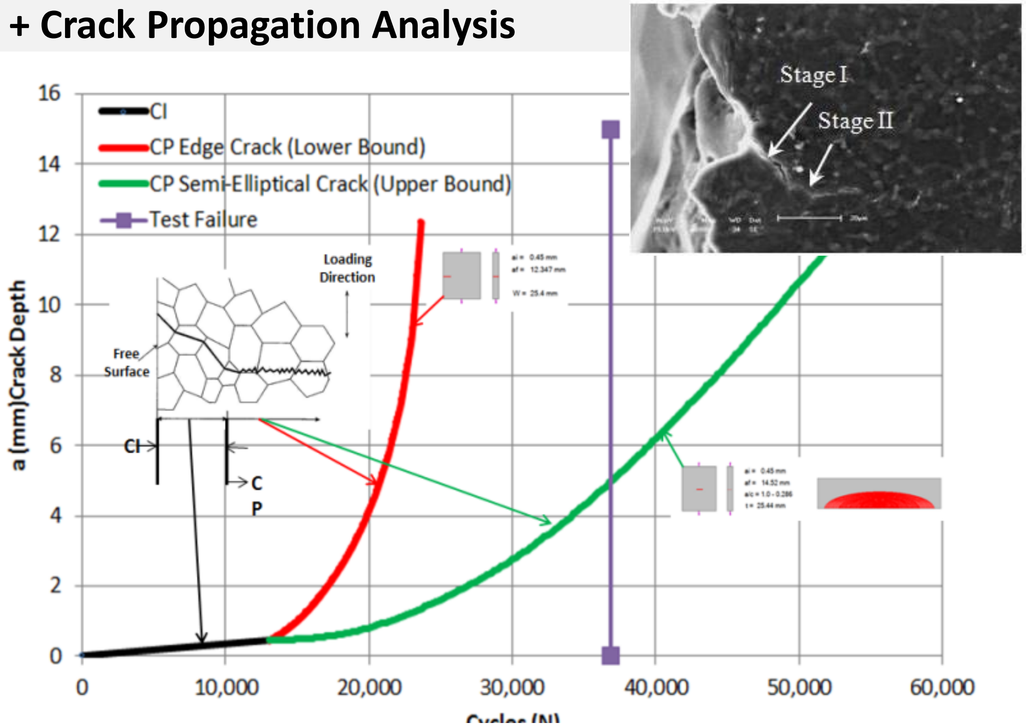


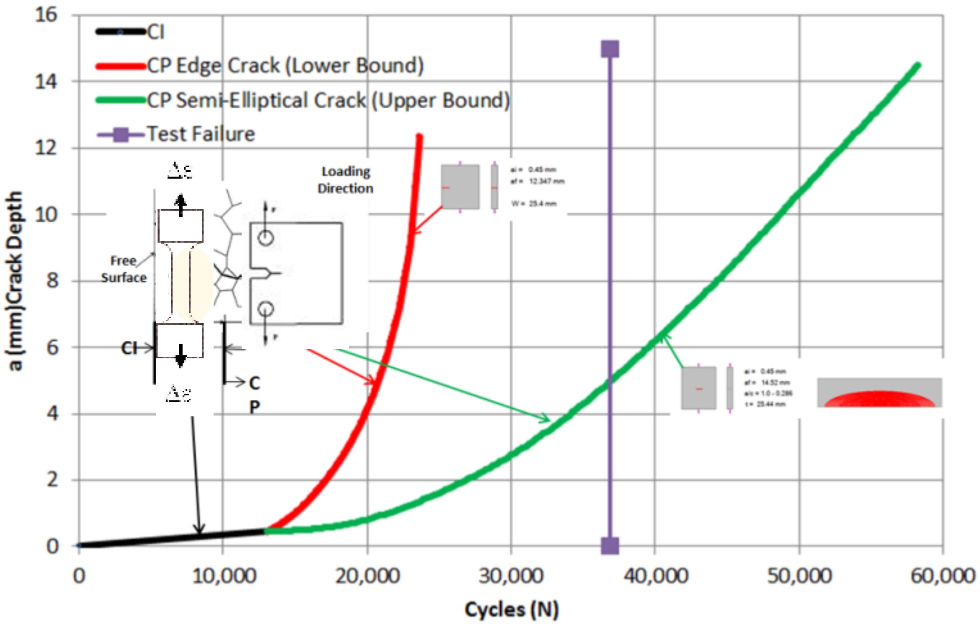
Initiated crack depth into the material assumed to be approximately three 0.049mm grain diameters =.147mm



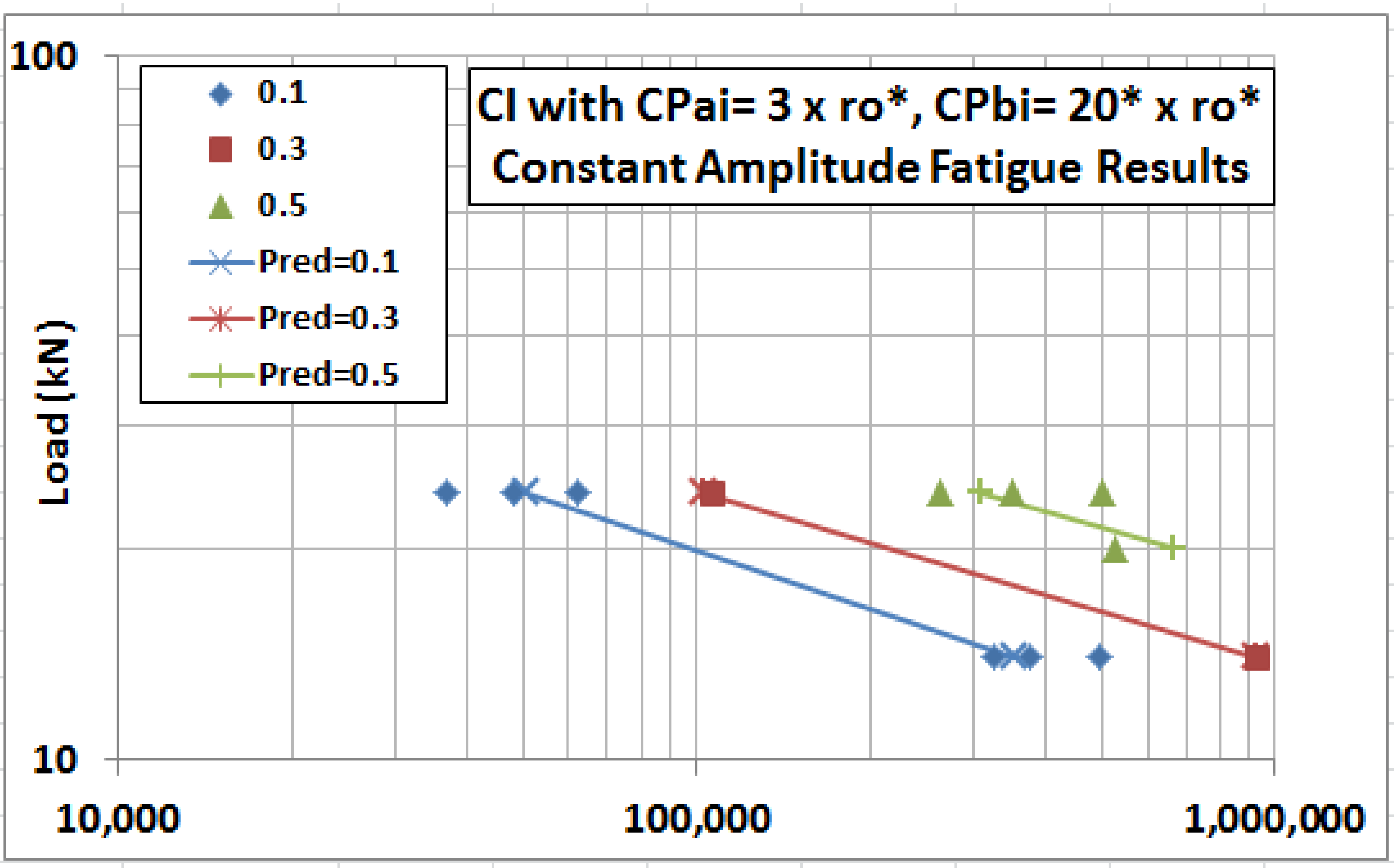
Total Fatigue Life – Combining the Crack Initiation + Crack Propagation Analysis





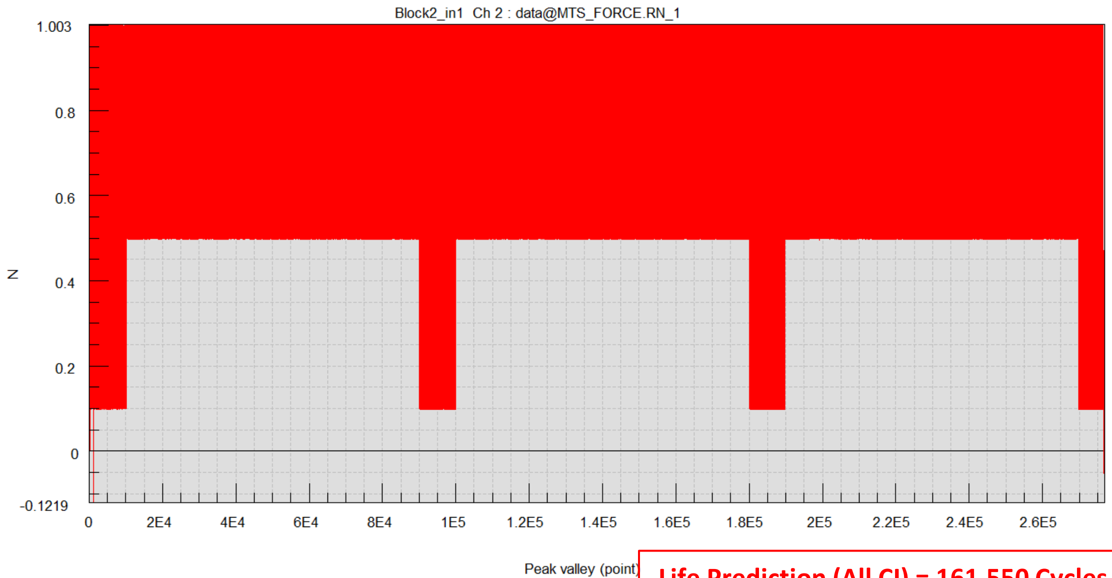


Total Fatigue Life: Crack Initiation + Crack Propagation Analysis



Block Cycle Crack Propagation – Demonstrates Changing Crack Aspect Ratio (a/c) During Propagation

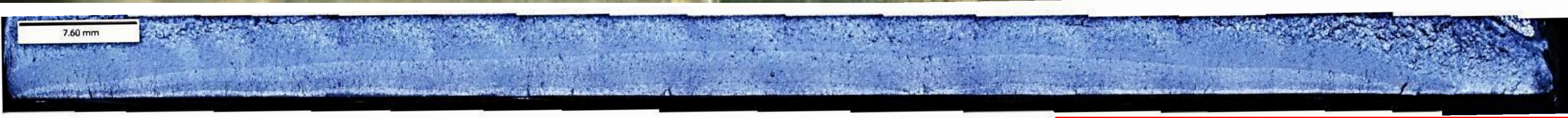
Recorded Test Load History/24 kN (5,000 R=0.1 / 40,000 R=0.5 Cycles Block History)



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-?
20	0.5	Constant Amplitude	529,250	4-4?
17	0.5	Constant Amplitude	4,900,000 NC*	5-1
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
24	0.1/0.5	Block Loading	138,421	4-1

*Note (NC): No crack growth found visually or by magnaflow

Life Prediction (All CI) = 161,550 Cycles
161,550(CI)/138,421 = 1.17 x Test Life



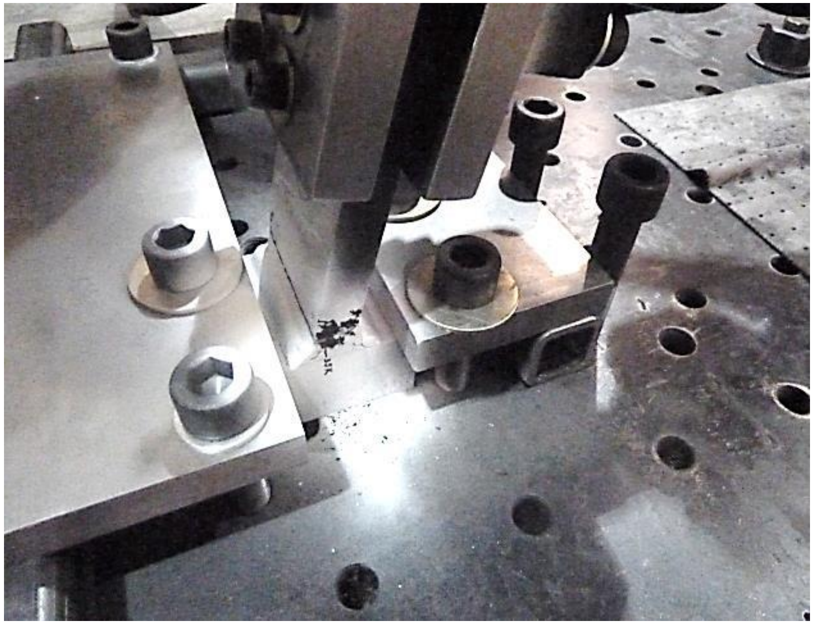
Observations:
1) The crack does not nucleate as a full width edge crack.
2) There appear to be multiple cracks "linking up or merging"
3) The crack aspect ratio changes continuously as the crack propagates through the thickness

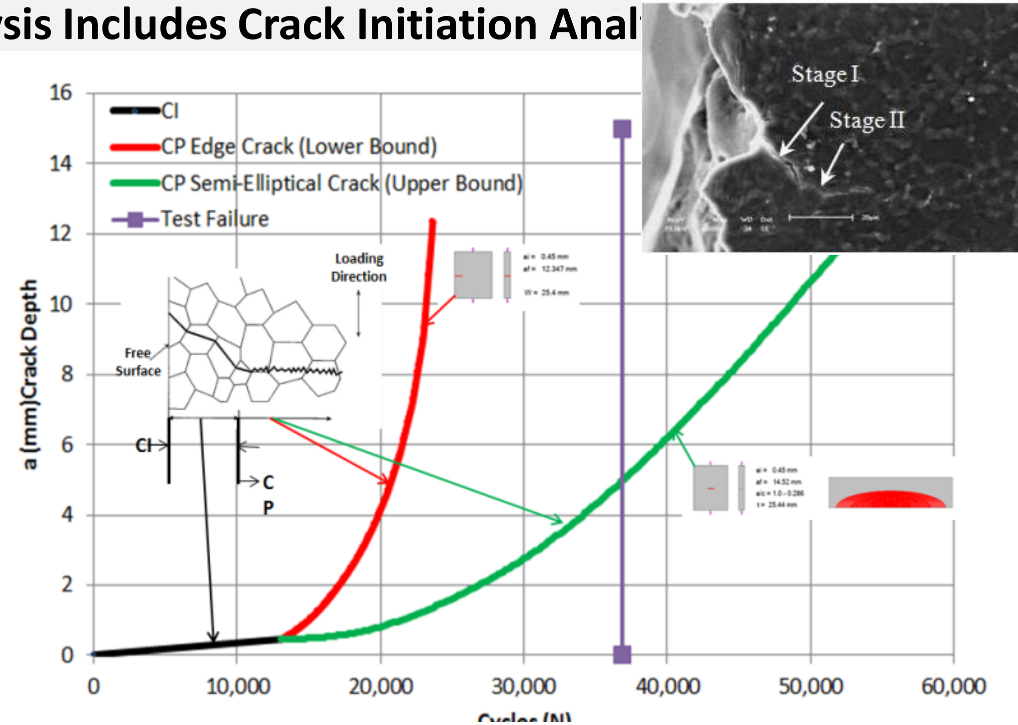
DISCRIMINATING TEST:
The analysis correlates well with the data but does not agree with physical observations of the fracture surface. The analysis life is all crack initiation.

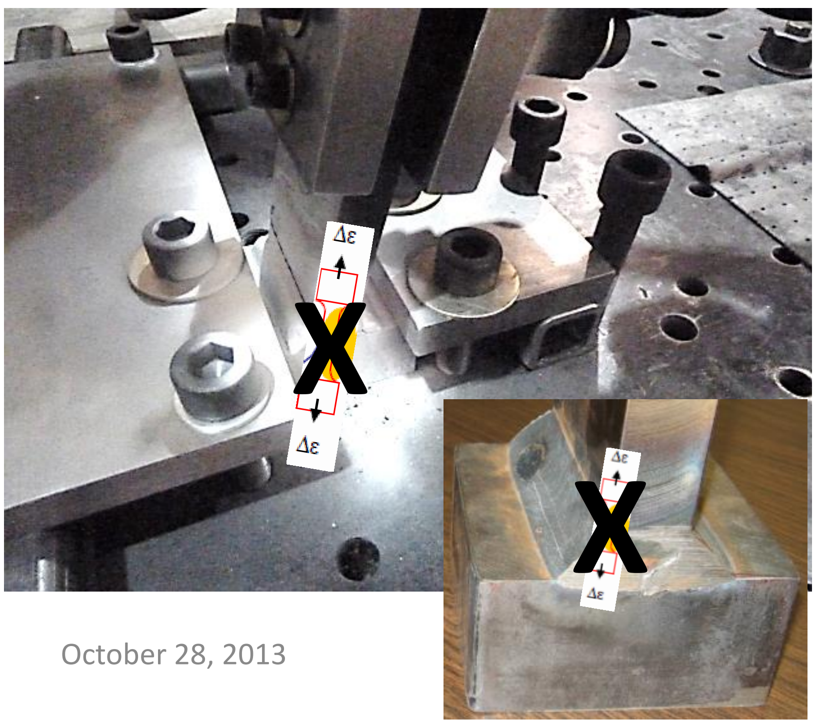
Analysis #2

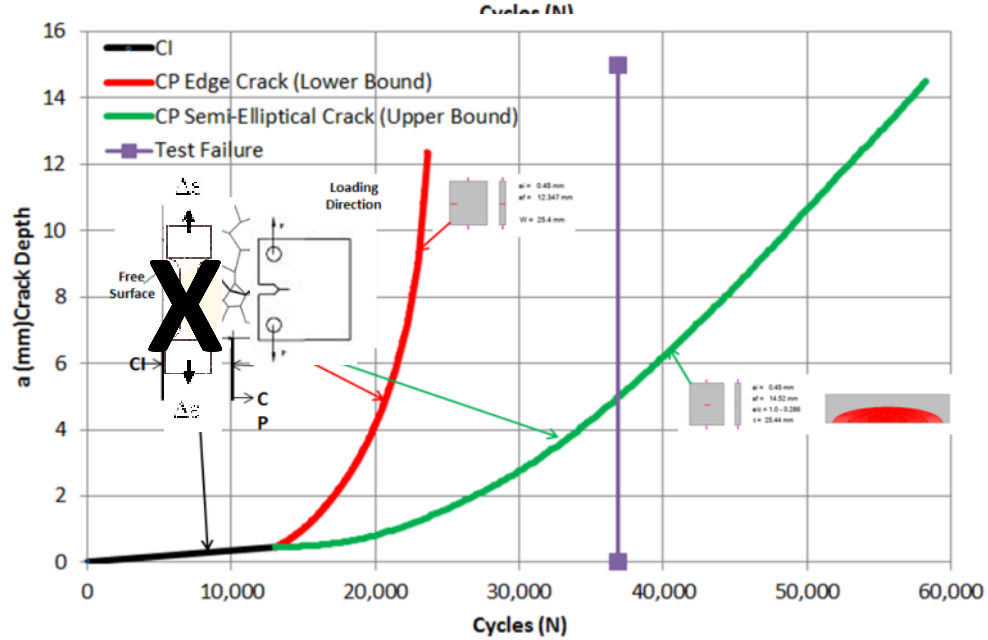
Semyon Mikheevskiy
Mechanical Engineer at SaFFD
University of Waterloo: Research Associate/Postdoctoral Fellow/Research Teaching Assistant

Total Fatigue Life – Crack Propagation Analysis Includes Crack Initiation Anal

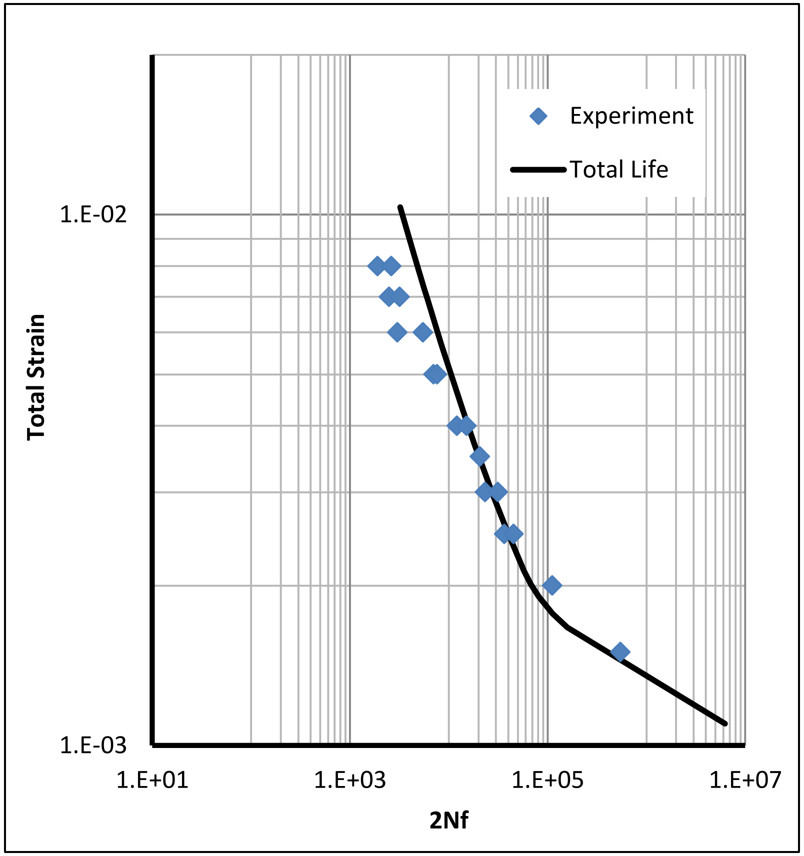








Validation for CA loading (Smooth specimen)



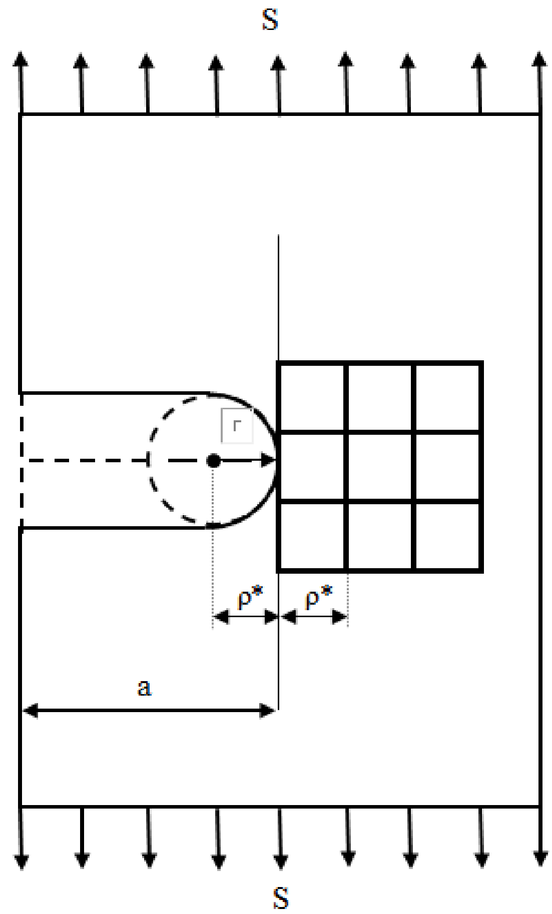
		Experiment				Total Life	
	De/2	Ds/2	2Nf		Ds/2	De/2	2Nf
0.010176	0.0070	417.1895	2483.0000		417.1895	0.01032285	3231.265659
0.011574	0.0080	398.3312	1905.0000		398.3312	0.00837931	4479.417536
0.009891	0.0080	385.3233	2634.0000		385.3233	0.00725086	5648.104989
0.009051	0.0070	381.7956	3175.0000		381.7956	0.00697165	6020.318006
0.009255	0.0060	364.6119	3029.0000		364.6119	0.00575901	8264.646475
0.007033	0.0060	361.8008	5494.0000		361.8008	0.00558224	8712.716505
0.00631	0.005	353.8015	7023		353.8015	0.00510956	10140.50291
0.006095	0.0050	337.1966	7604.0000		337.1966	0.00425926	13997.35818
0.005016	0.004	323.9506	12075		323.9506	0.00369222	18233.88394
0.004578	0.0040	311.1283	15143.0000		311.1283	0.00322401	23702.14806
0.003872	0.003	302.9740	23362		302.9740	0.0029626	28097.06112
0.004055	0.0035	290.4376	20669.0000		290.4376	0.00260913	36680.75063
0.003295	0.0025	286.014235	36480		286.01424	0.00249707	40358.29674
0.00306	0.0025	283.5924	45239		283.5924	0.00243831	42539.68847
0.003472	0.0030	282.6485	31461.0000		282.6485	0.00241588	43424.23432
0.002305	0.002	269.62637	111751		269.62637	0.00213213	57890.61118
0.001547	0.0015	263.5425	546702		263.5425	0.00201459	67433.83733
0.002815	0.0025	257.5792	58177.0000		257.5792	0.00190768	81206.13698
0.001771	0.0018	250.1759	302231.0000		250.1759	0.00178544	108443.0407
0.002252	0.0020	249.3594	121105.0000		249.3594	0.00177262	112426.6948
0.001471	0.0015	242.4798	691501.0000		242.4798	0.0016695	157412.8858

- Experimental Strain-Life data was provided by JD
- FCG constants (C, gamma) were found on previous slide
- Set initial semi-circular crack with a=b=ρ* in 8mm smooth specimen
- Run total life approach for each stress level and obtain the fatigue life
- Good correlation with experimental data
- Shows the ability of Total Life Approach to predict M-C curve using FCG data

Basics Assumptions

- The crack is modeled as a sharp notch with finite tip radius ρ*.
- Material is modeled as made from elementary material blocks. Fatigue crack growth is regarded as successive crack increments (re-initiation) over distance ρ*.
- The number of cycles N* necessary to break the material over the distance ρ* can be determined from the cyclic (Ramberg-Osgood) and fatigue material curve (Manson-Coffin)
- The instantaneous fatigue crack growth rate can be determined as:

$$\frac{da}{dN} = \frac{\rho^*}{N^*}$$



Total Fatigue Life – Crack Propagation Analysis Includes Crack Initiation 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)

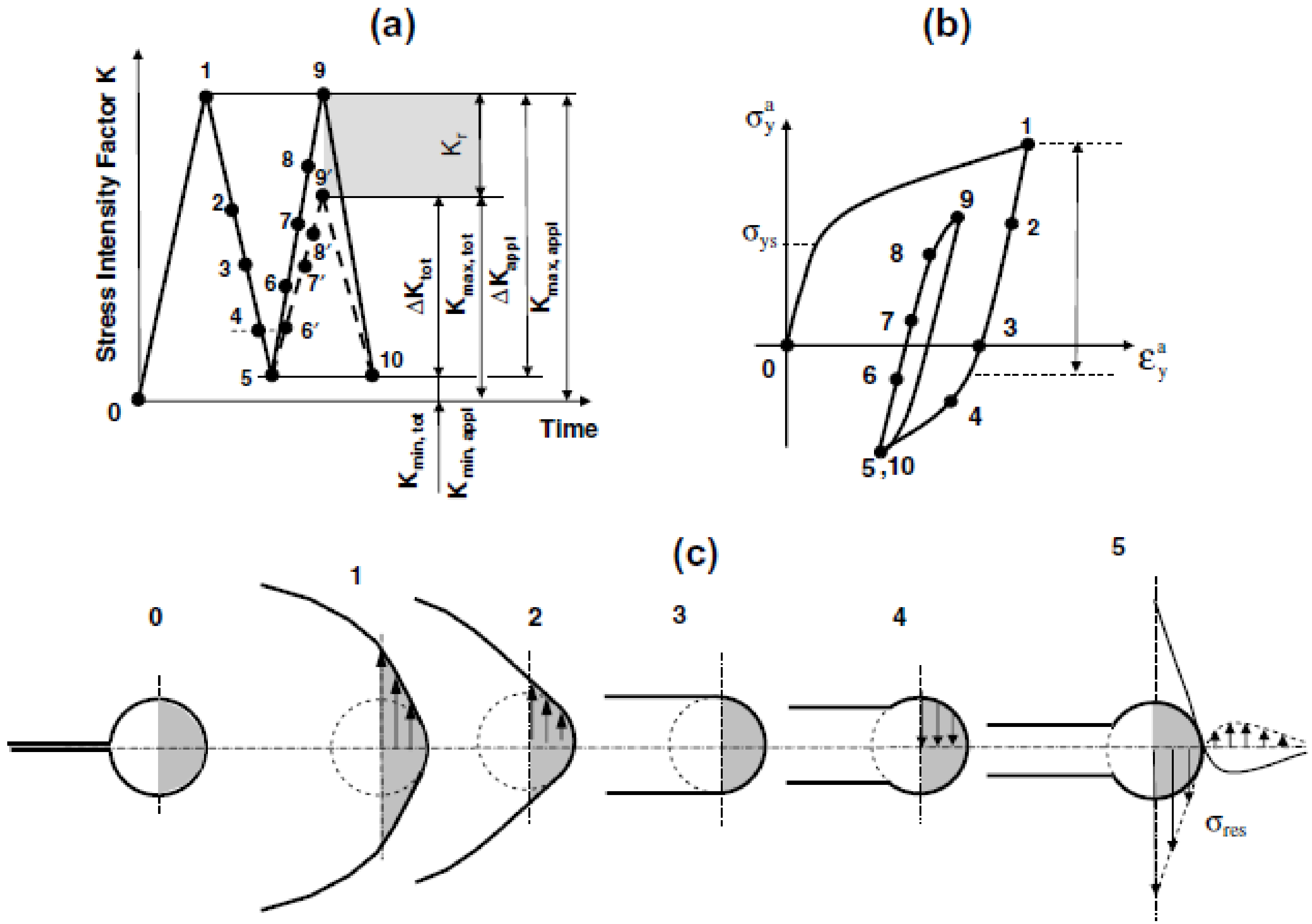


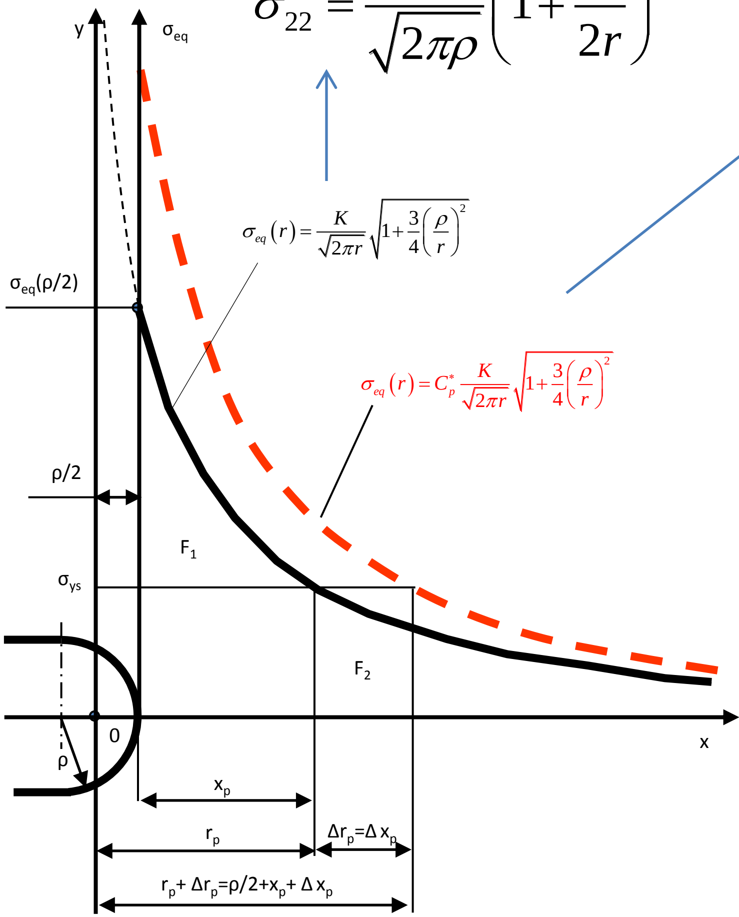
Fig. 1. Schematic crack tip geometry and displacement field, cyclic plastic zone, crack tip stress–strain response and the residual stress distribution: (a) applied load (stress intensity factor) history, (b) qualitative stress–strain response at crack tip, and (c) evolution of the crack opening displacements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

New plastic zone correction C_p

Use S_{22} stresses instead of S_{eq}

$$\sigma_{22} = \frac{K}{\sqrt{2\pi\rho}}\left(1+\frac{\rho}{2r}\right)$$

$$\sigma_{22} = C_p \frac{K}{\sqrt{2\pi\rho}}\left(1+\frac{\rho}{2r}\right)$$

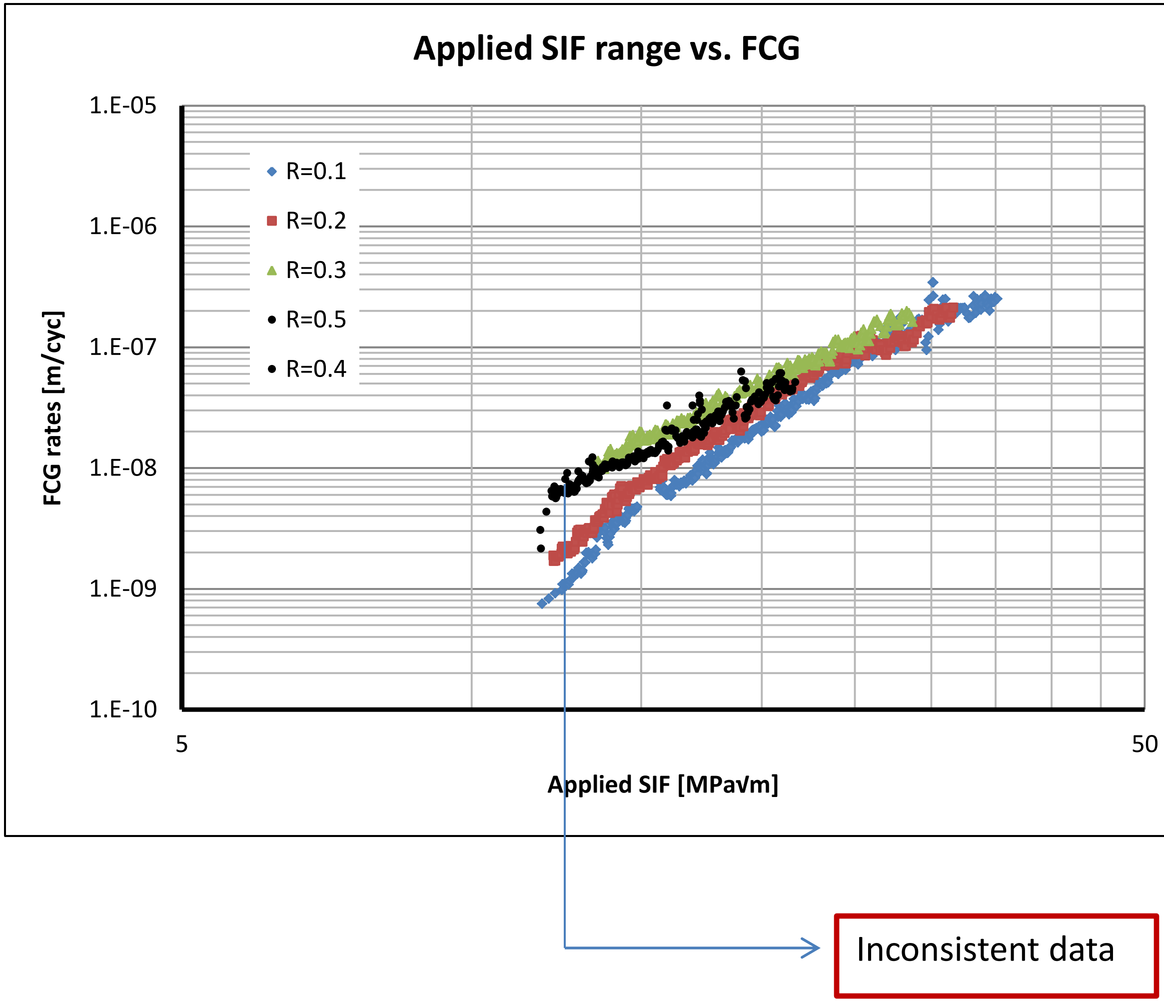


- Elastic stresses ahead of the notch/crack should be redistributed due to the plastic deformations other X_p distance
- Original correction C_p was based on the equivalent stress
- The main idea: the classical plastic zone should be extended by the amount DX_p such that $F_1=F_2$
- Finding F_1 area for each cycle of the loading history numerically is time consuming and the originally proposed method was found to be inconsistent (nCode)
- In order to avoid it, it was proposed to redistribute S_{22} stress component instead of the S_{eq}.
- The new method is supported by the fact that in the case of a crack the propagation is defined by the S_{22} not S_{eq}.
- It allows to find F_1 area analytically (no numerical errors) and reduces computational time

Total Fatigue Life – Crack Propagation Analysis Includes Crack Initiation Analysis

A36 Material Properties

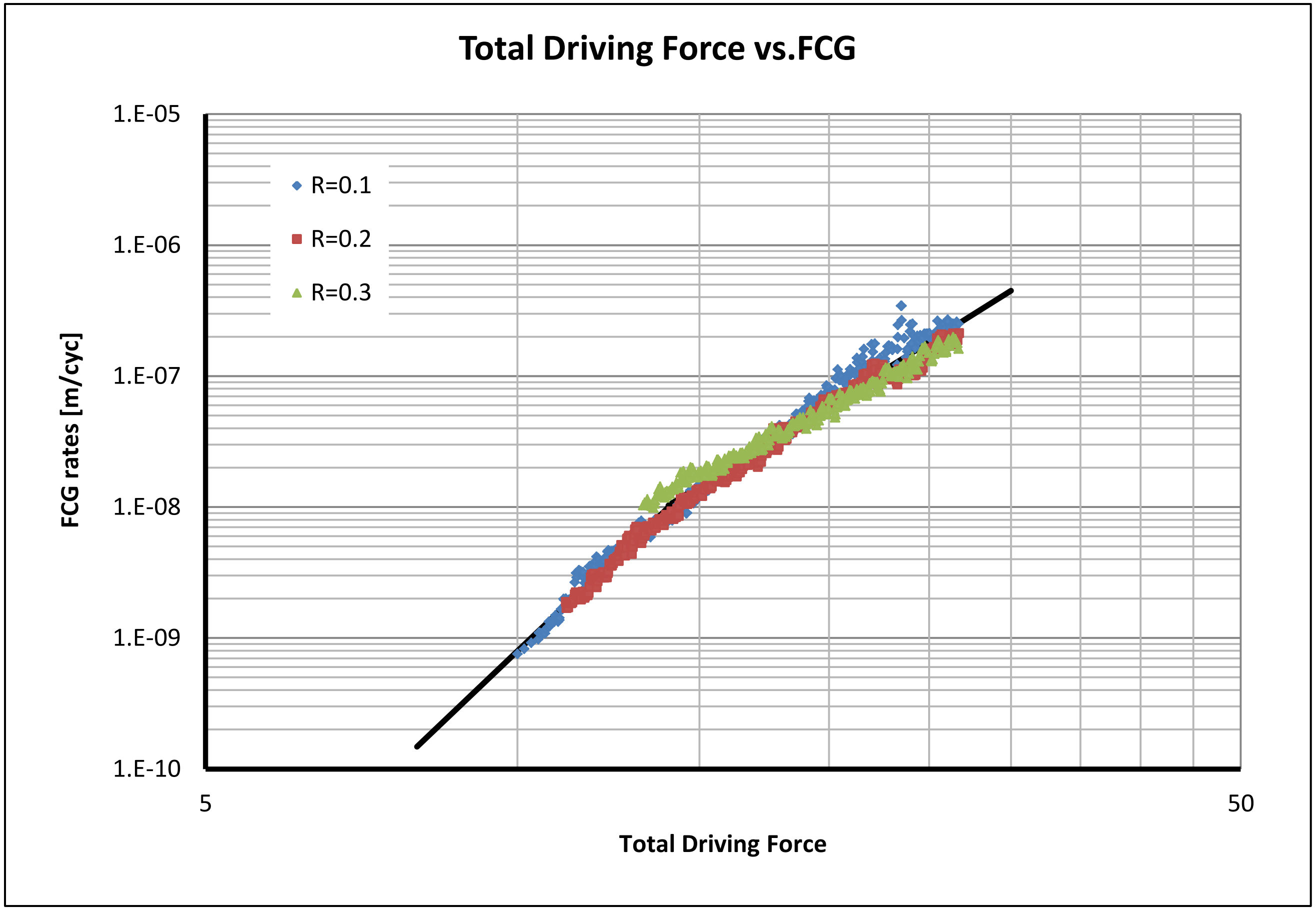
E	v	n'	K'	Sys	p	rho*
190786	0.3	0.1799	991.4	324.119	0.152471	7.27E-05



- FCG rates were measured for 5 different load ratios
- Data for R=0.4 and R=0.5 (black circles) looks suspicious since FCG rates are smaller than for R=0.3
- Only R=0.1, R=0.2, and R=0.3 data will be used in the analysis

A36 FCG data in terms of Total Driving Force

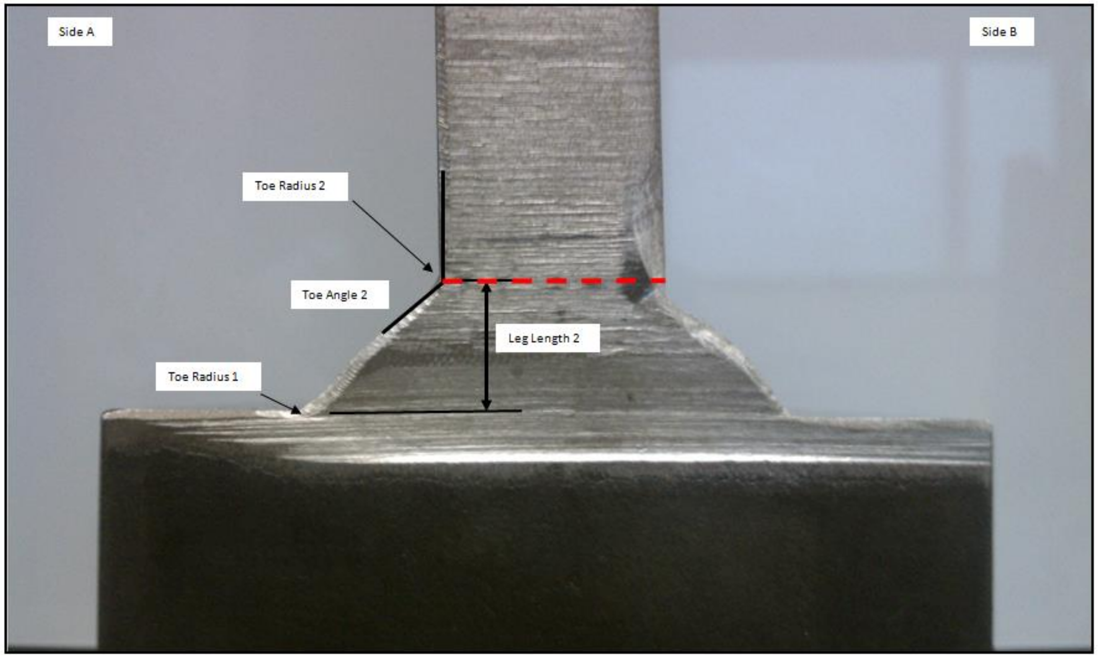
C1	Gamma1	COV1	C2	Gamma2	COV2
1.39E-18	8.73392	0.05681	3.38E-13	3.97455	0.046464

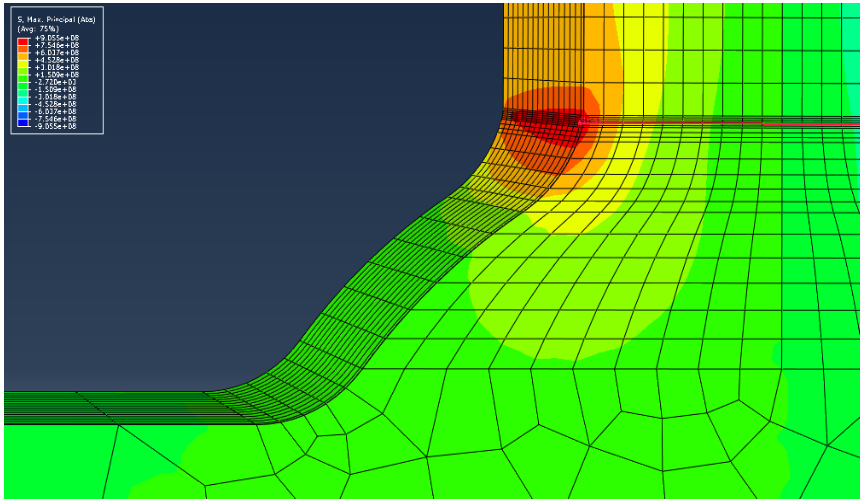


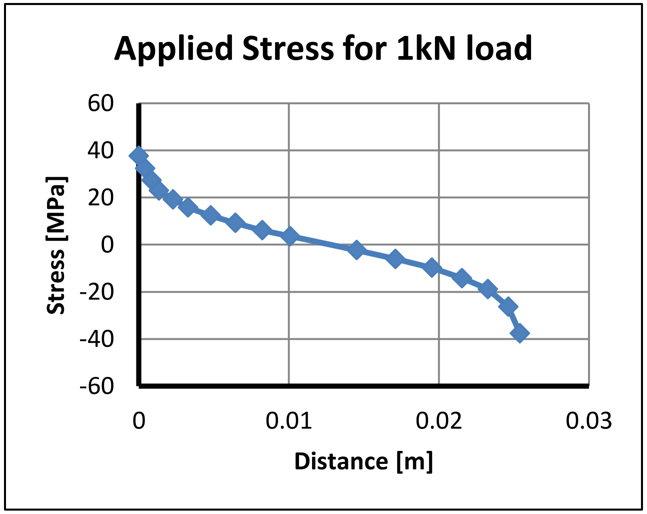
Based on the new Cp correction, the best collapse of FCG was obtained for r* = 7.27E-05.

$$TotalDrivingForce = \left(\Delta K_{appl} - K_r\right)^{1-p}\left(K_{\max,appl} - K_r\right)^{p}$$

Validation for CA loading (Welded specimen)



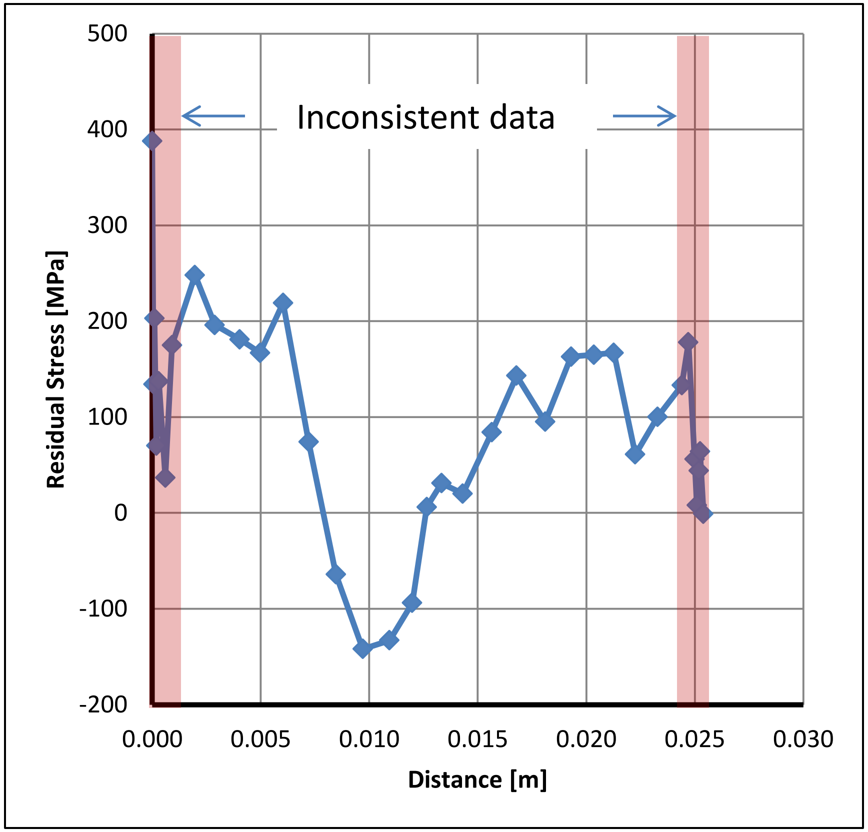




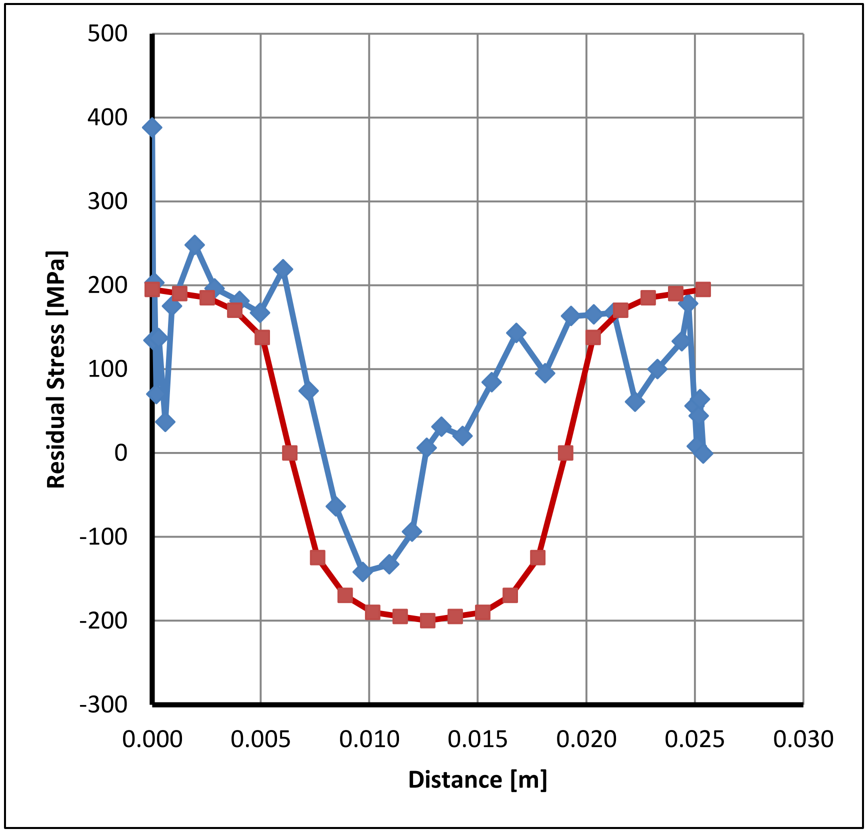
Total Fatigue Life – Crack Propagation Analysis Includes Crack Initiation Analysis

Residual Stress Field

- Data becomes slightly inconsistent close to the surface layer
- Residual stress field is not in equilibrium

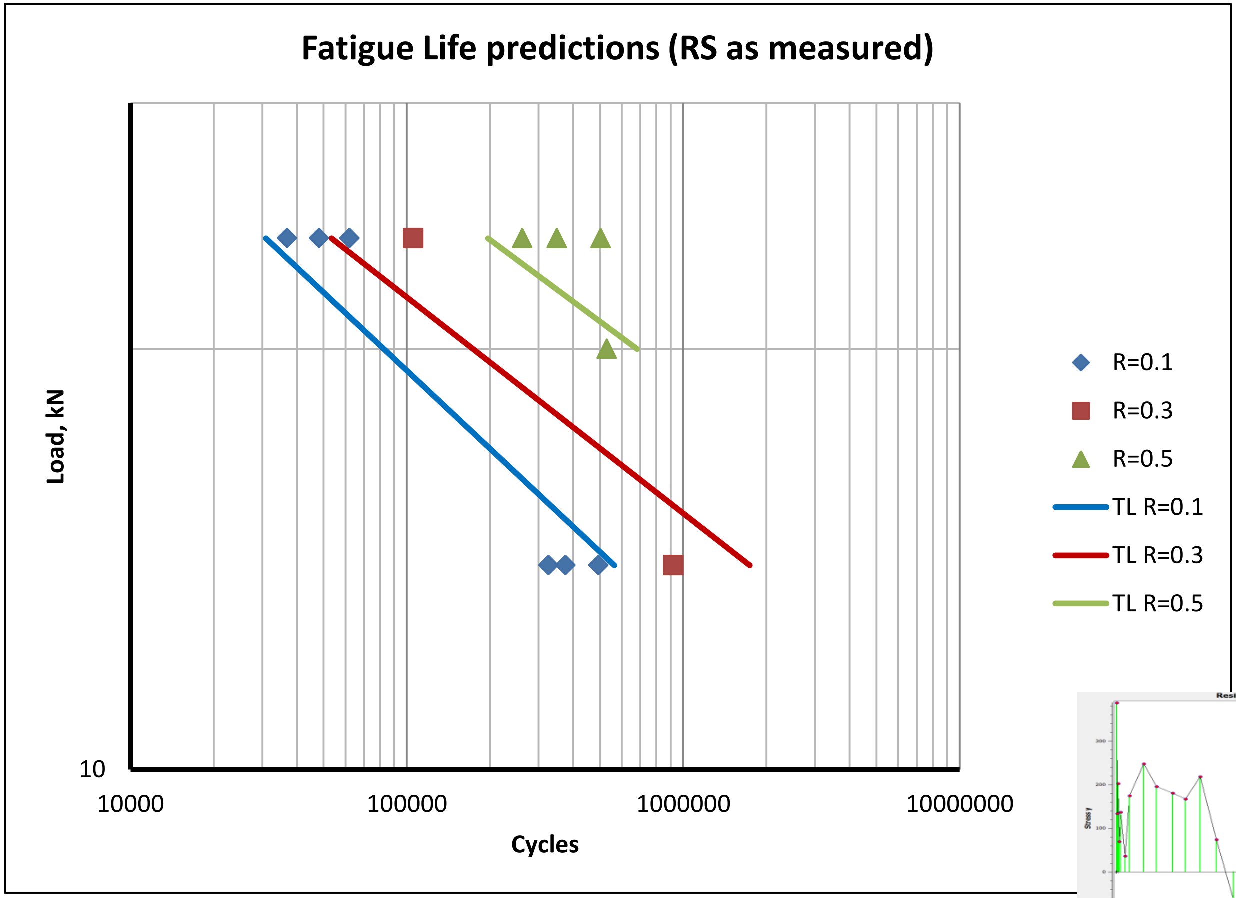


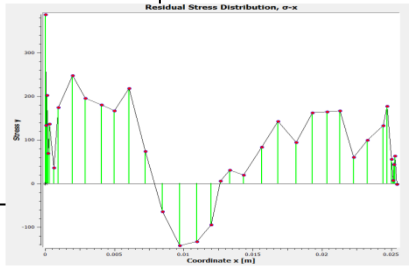
- Modified residual stress field with smooth ends and in equilibrium



Total Fatigue Life – Crack Propagation Analysis Includes Crack Initiation Analysis

FCG analysis using Total Life and RS as measured

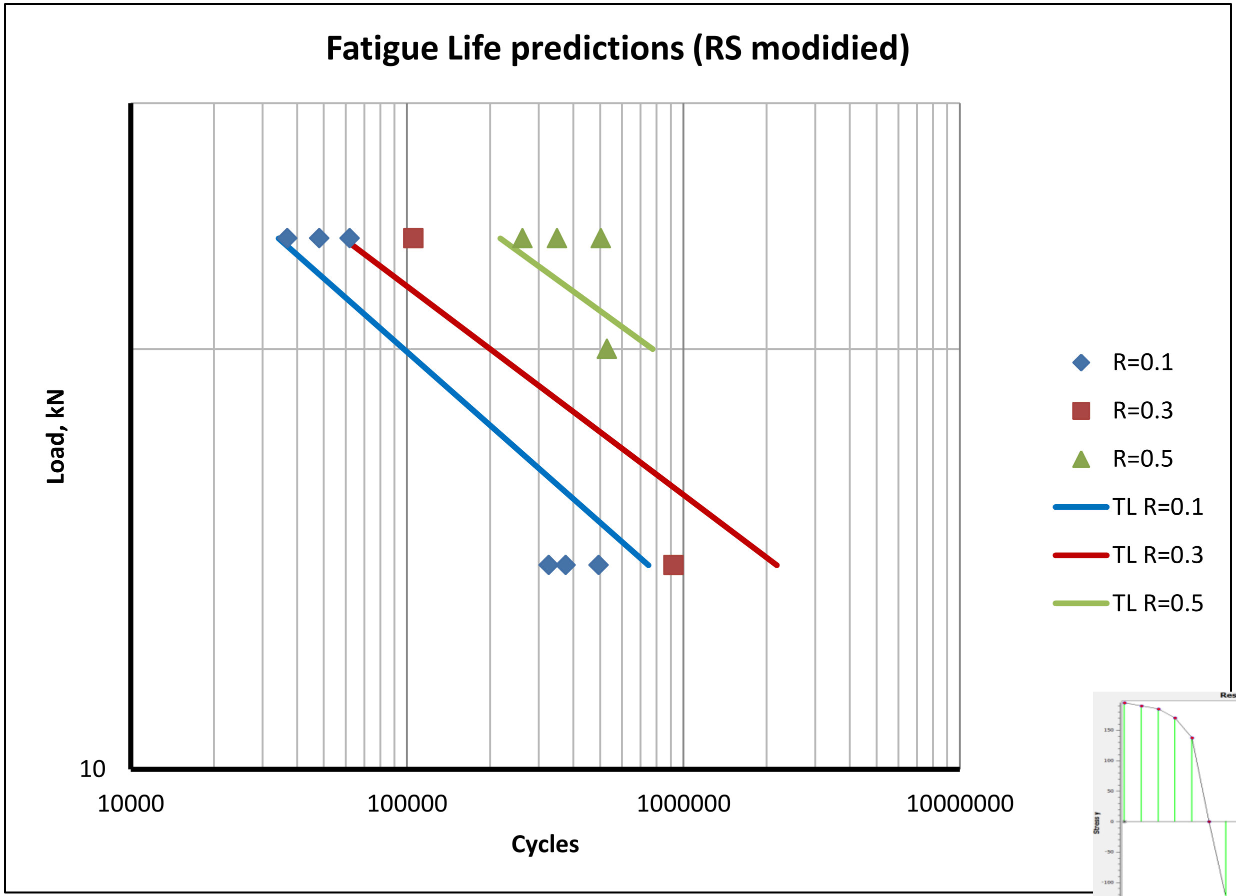


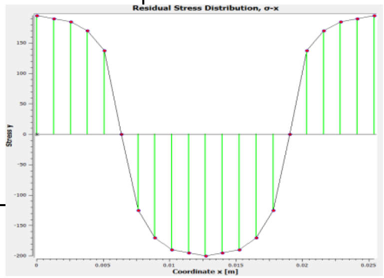


- Total life approach was run with initial semi-circular crack with a=b=ρ* until failure
- R=0.1, R=0.3, and R=0.5 were used
- L=24kN, L=20kN, and L=14kN were used
- OK life estimation for R=0.1 and R=0.5, less than twice of for R=0.3

Total Fatigue Life – Crack Propagation Analysis Includes Crack Initiation Analysis

FCG analysis using Total Life and RS modified

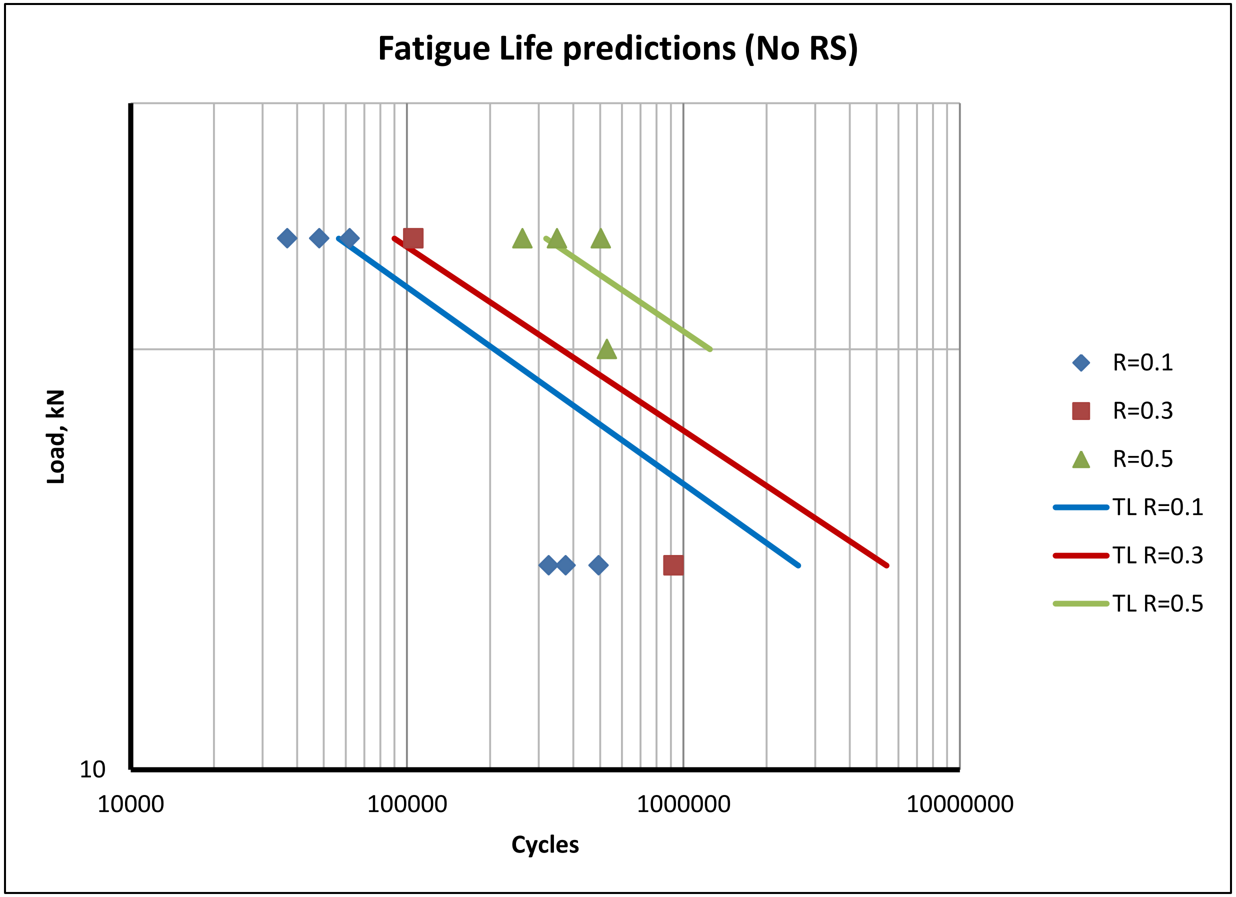




- Total life approach was run with initial semi-circular crack with a=b=ρ* until failure
- R=0.1, R=0.3, and R=0.5 were used
- L=24kN, L=20kN, and L=14kN were used
- Very similar results as for RS measured, slightly longer life in all cases

Total Fatigue Life – Crack Propagation Analysis Includes Crack Initiation Analysis

FCG analysis using Total Life no RS

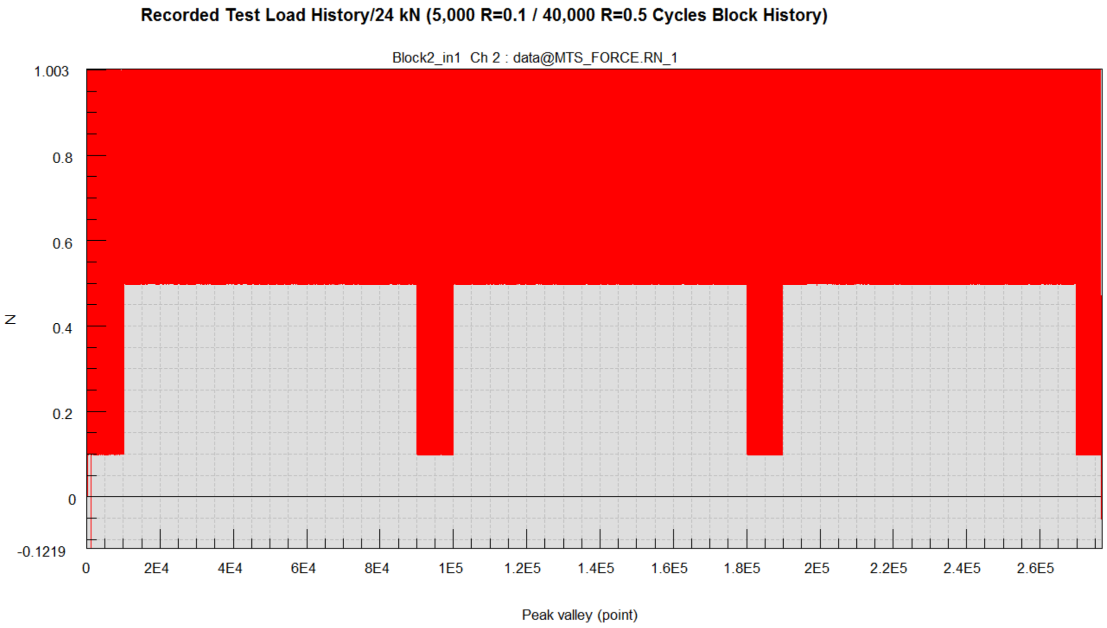


• Good predictions for L=24kN which shows little importance of RS if applied load is very high. High loads produce enough stresses to make RS less important.

• Bad predictions if applied load is not that high. Life is approximately 5 times longer than experimental.

Total Fatigue Life – Crack Propagation Analysis Includes Crack Initiation Analysis

Validation for Block loading (Welded specimen)



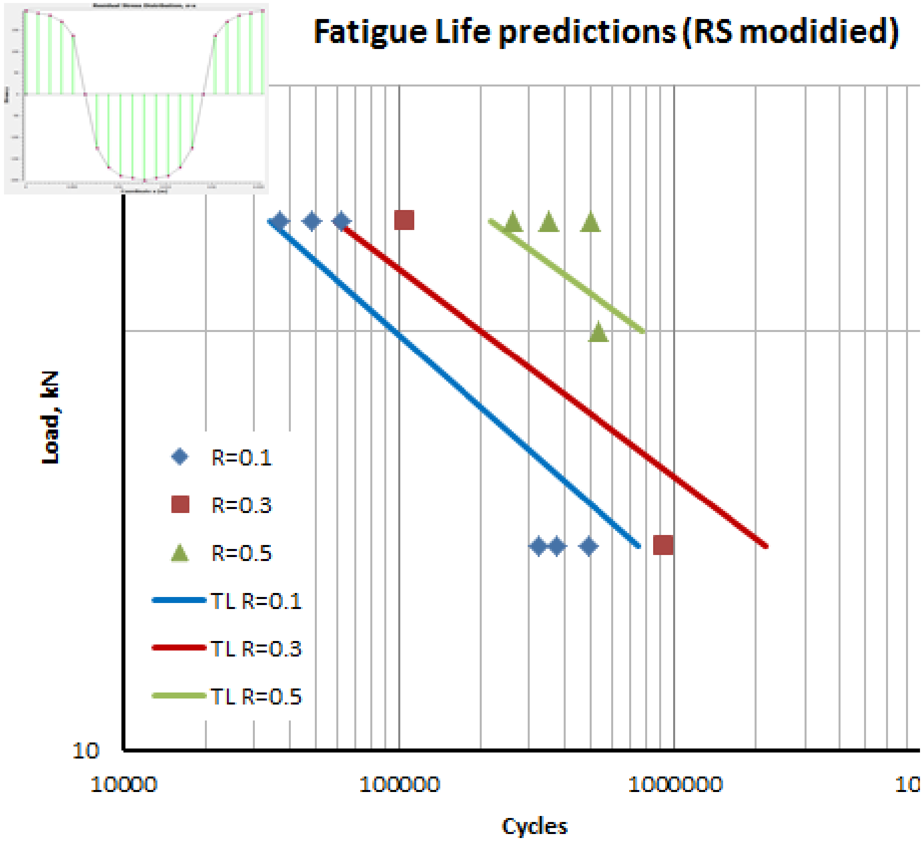
RS as measured: Life = 135,670/138,421 = 0.98

RS modified: Life = 136,979/138,421= 0.99

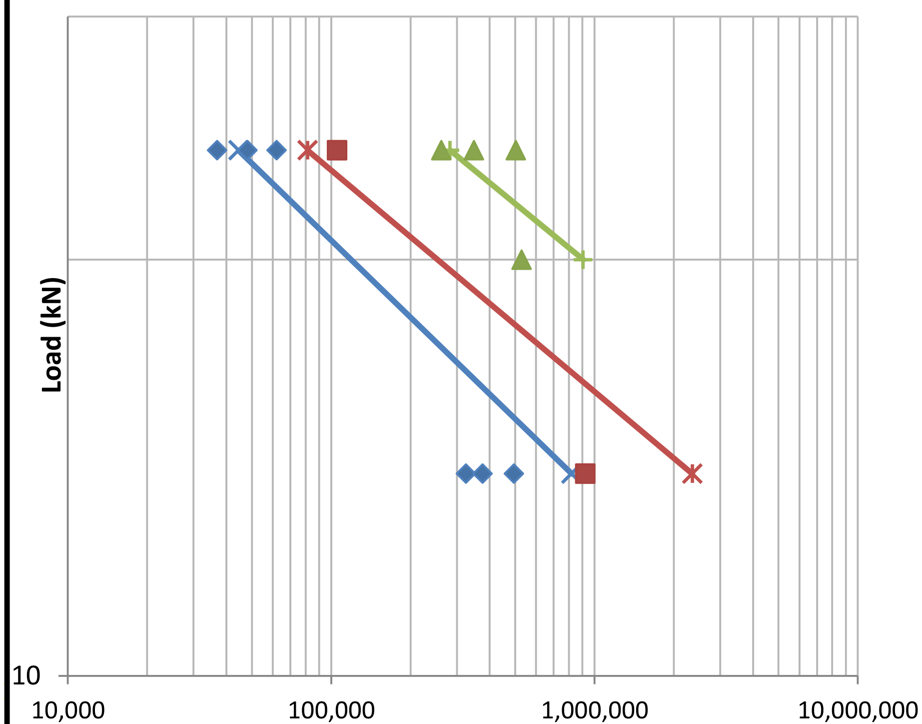
DISCRIMINATING TEST:
The analysis correlates well with the data and agrees with physical observations of the fracture surface.
The analysis life is all crack propagation

Redo Tom's Crack Initiation + Crack Propagation Analysis With Semyon's Analysis Inputs

Semyon's
"Crack Initiation Included in Crack Propagation"
Method



Tom's
"Crack Initiation + Crack Propagation"
Method

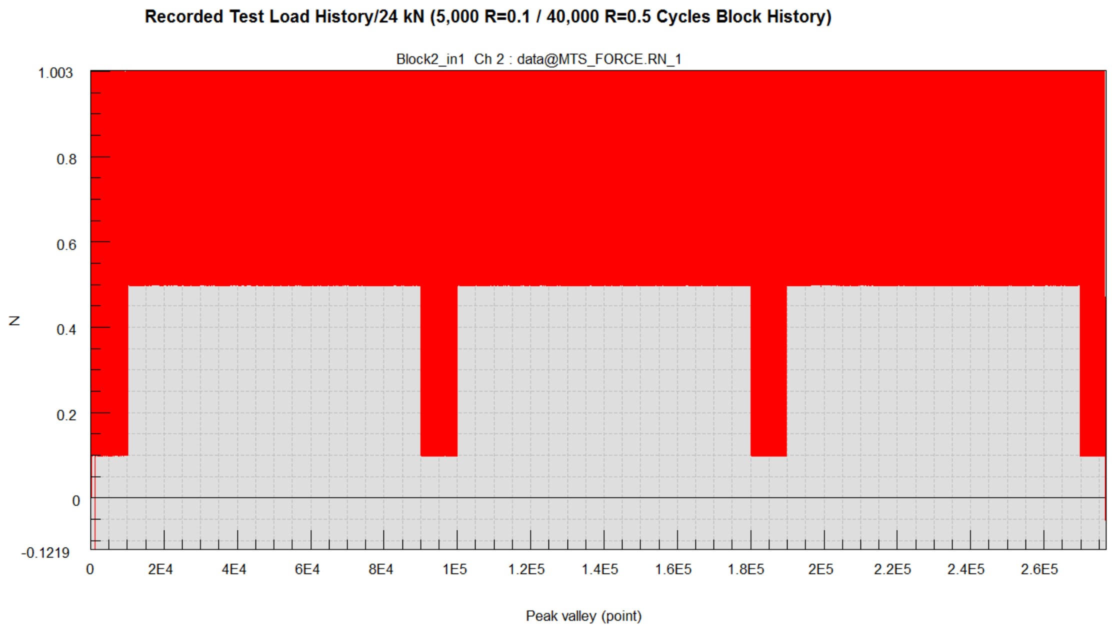


The Difference Is Not In The Analysis Methodologies, *It's In The Inputs Into The Methodologies*

Total Fatigue Life: Crack Initiation and Crack Propagation Analysis

Redo Tom's Crack Initiation + Crack Propagation Analysis With Semyon's Analysis Inputs

Validation for Block loading (Welded specimen)



Semyon's Crack Propagation Analysis Includes Crack Initiation Analysis RS modified: Life = 136,979/138,421= 0.99

Redo Tom's Crack Initiation + Crack Propagation Analysis With Semyon's Analysis Inputs RS modified: Life = 178,811/138,421 = 1.29

The Difference Is Not In The Analysis Methodologies, *<u>It's In The Inputs Into The Methodologies</u>*