Predicting Total Fatigue Life (Crack Initiation and Crack Propagation)

Presented at HBM-nCode (Southfield, MI)
on Monday 13 October 2014
(Prepared by Tom Cordes)

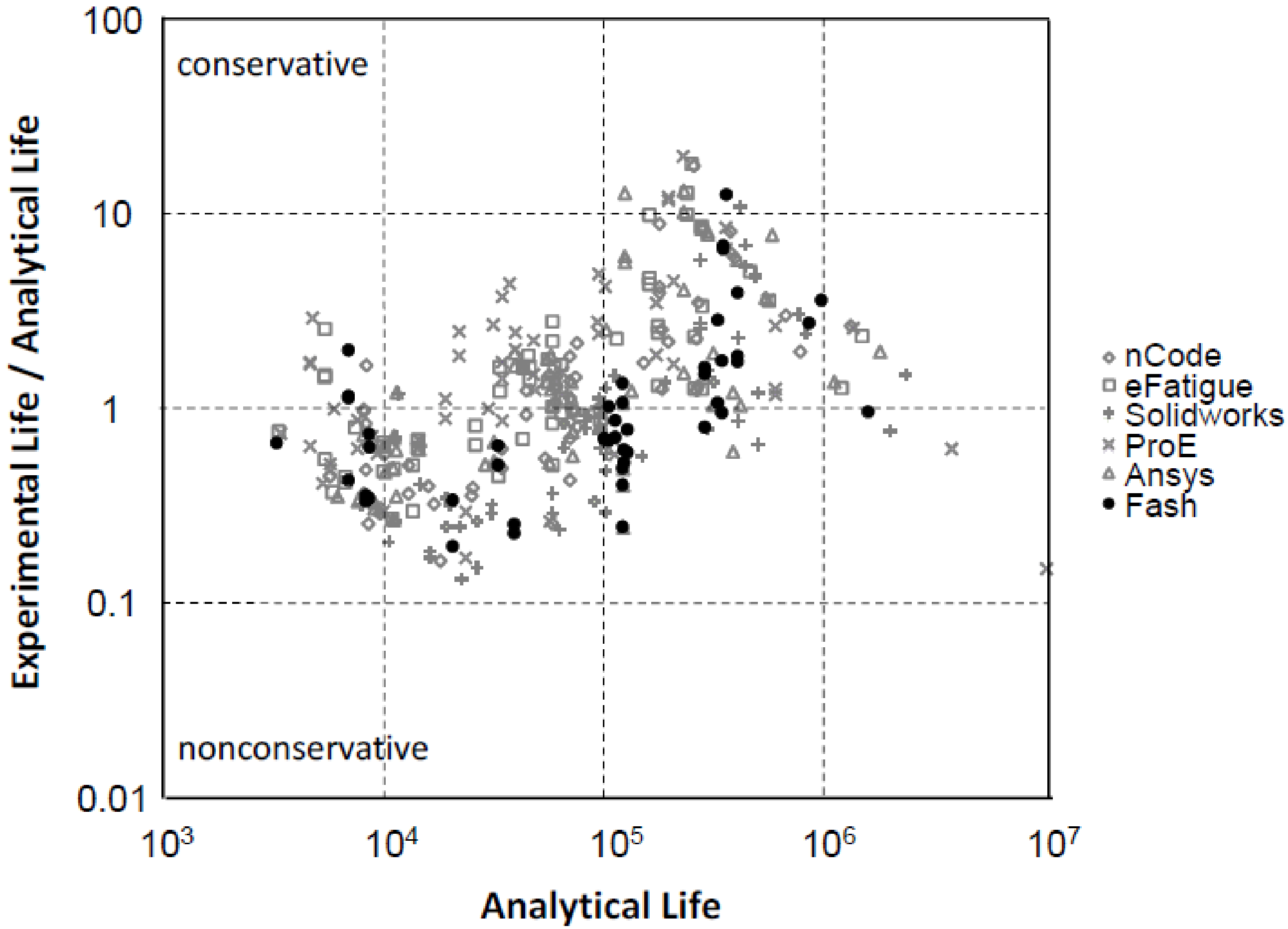
Total Fatigue Life: Crack Initiation and Crack Propagation

1. Introduction, Test Sample and Test Setup, and Test/Analysis Correlation (23 Slides)
2. Appendix A: Stress Distribution Information
3. Appendix B: Microstructure, CI and CP Material Property Information
4. Appendix C: Gregory Glinka CP Methodology Basic Background
5. Appendix D: Local Strain CI Methodology Basic Background
6. Appendix E: "First Round" Welded Sample Test/Analysis History
7. Appendix F: Address Simultaneous Front & Back Side R = -1.0 Crack
8. Appendix G: Block Loading Analysis
9. Appendix H: Variable Amplitude CI Life Un-Conservative Life Prediction
10. Appendix I: Fracture Surface Striation Measurement Methodology (68 Slides)

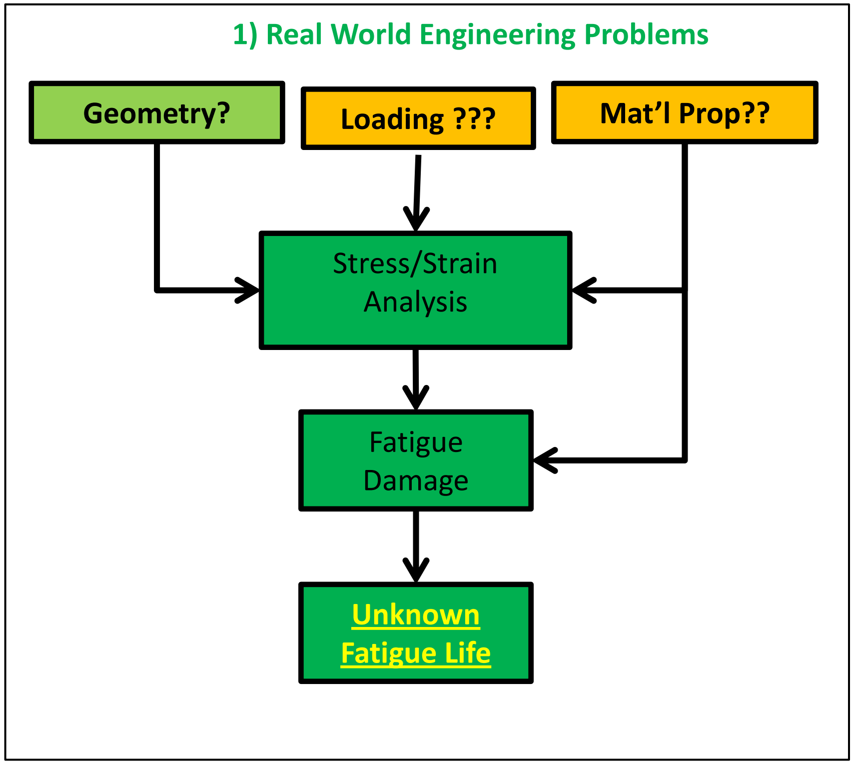
Total Fatigue Life: Crack Initiation and Crack Propagation

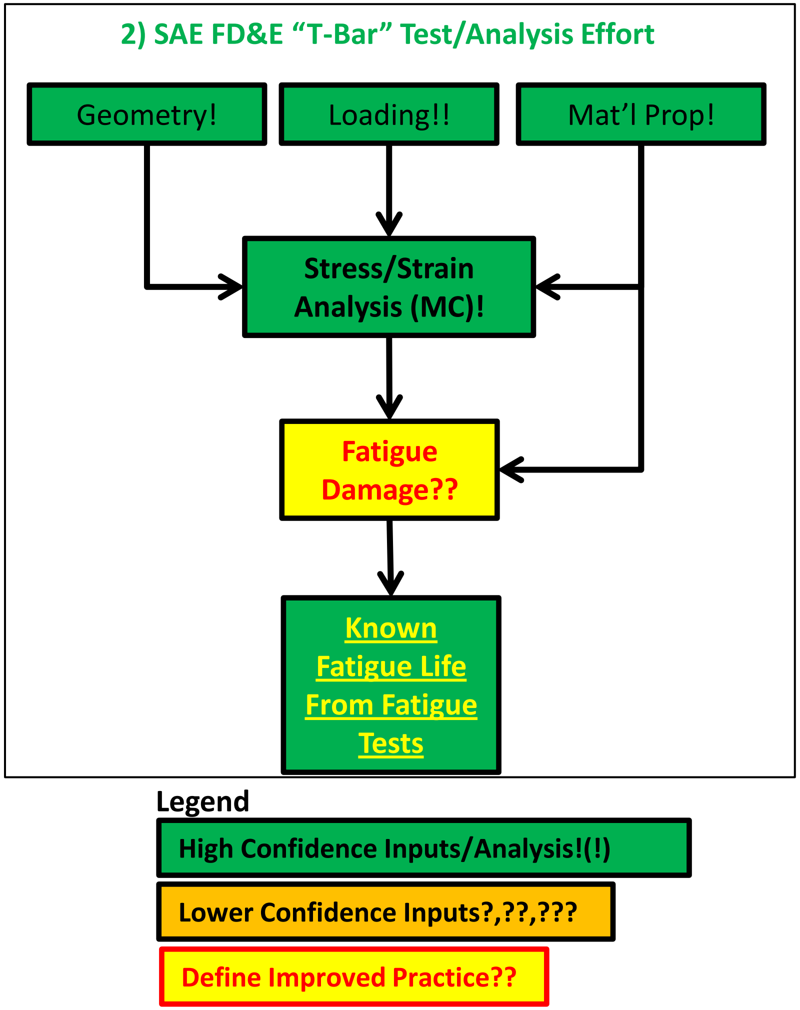
Previous SAE FD&E Analysis to Test Correlation Effort Results``

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



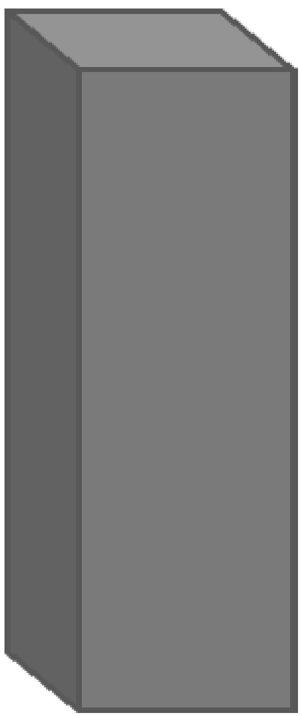


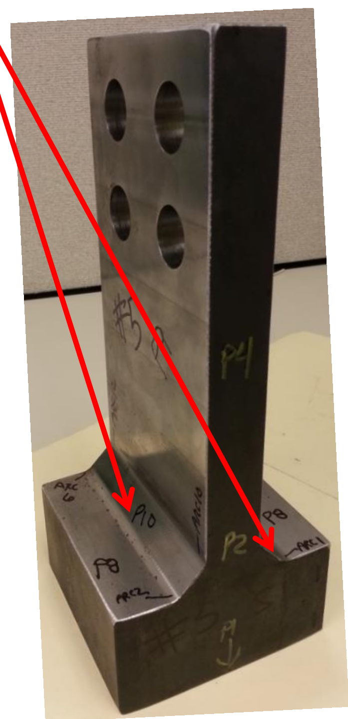
This effort is using "very well defined/controlled analysis inputs" to address an engineering problem to validate (or not) a potential <u>"Total Fatigue Life Prediction Improved Practice"</u>

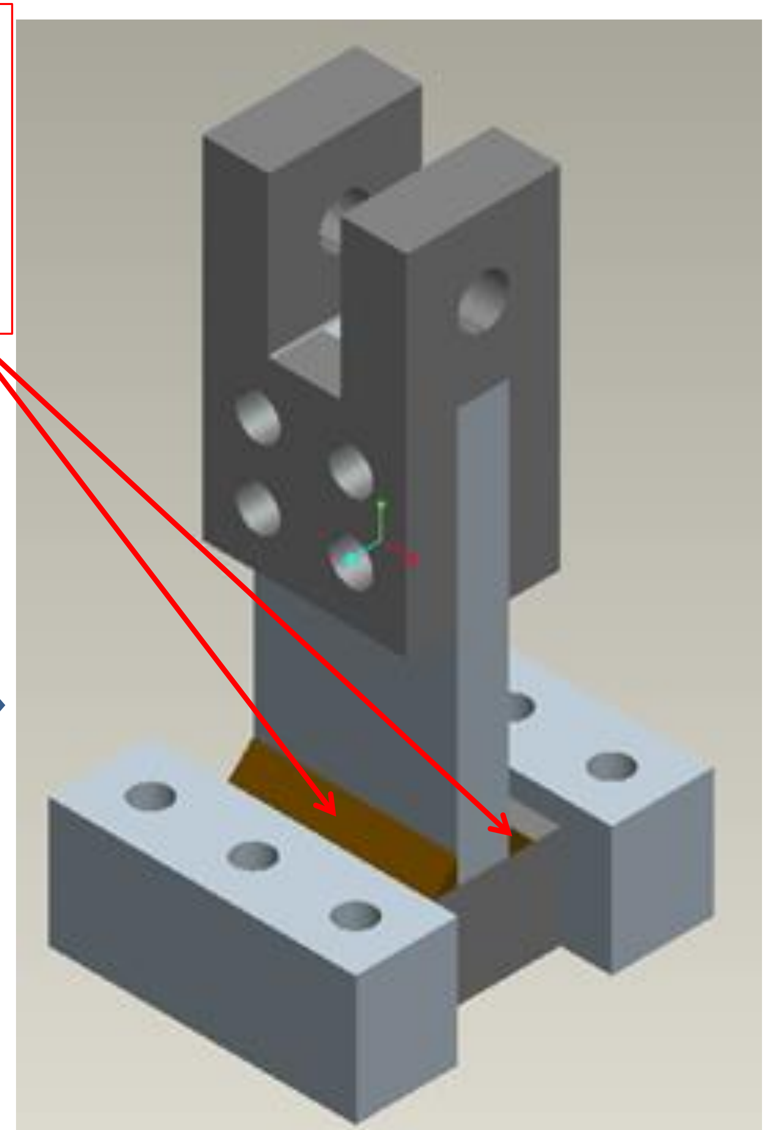
Total Fatigue Life: Crack Initiation and Crack Propagation Analysis

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.

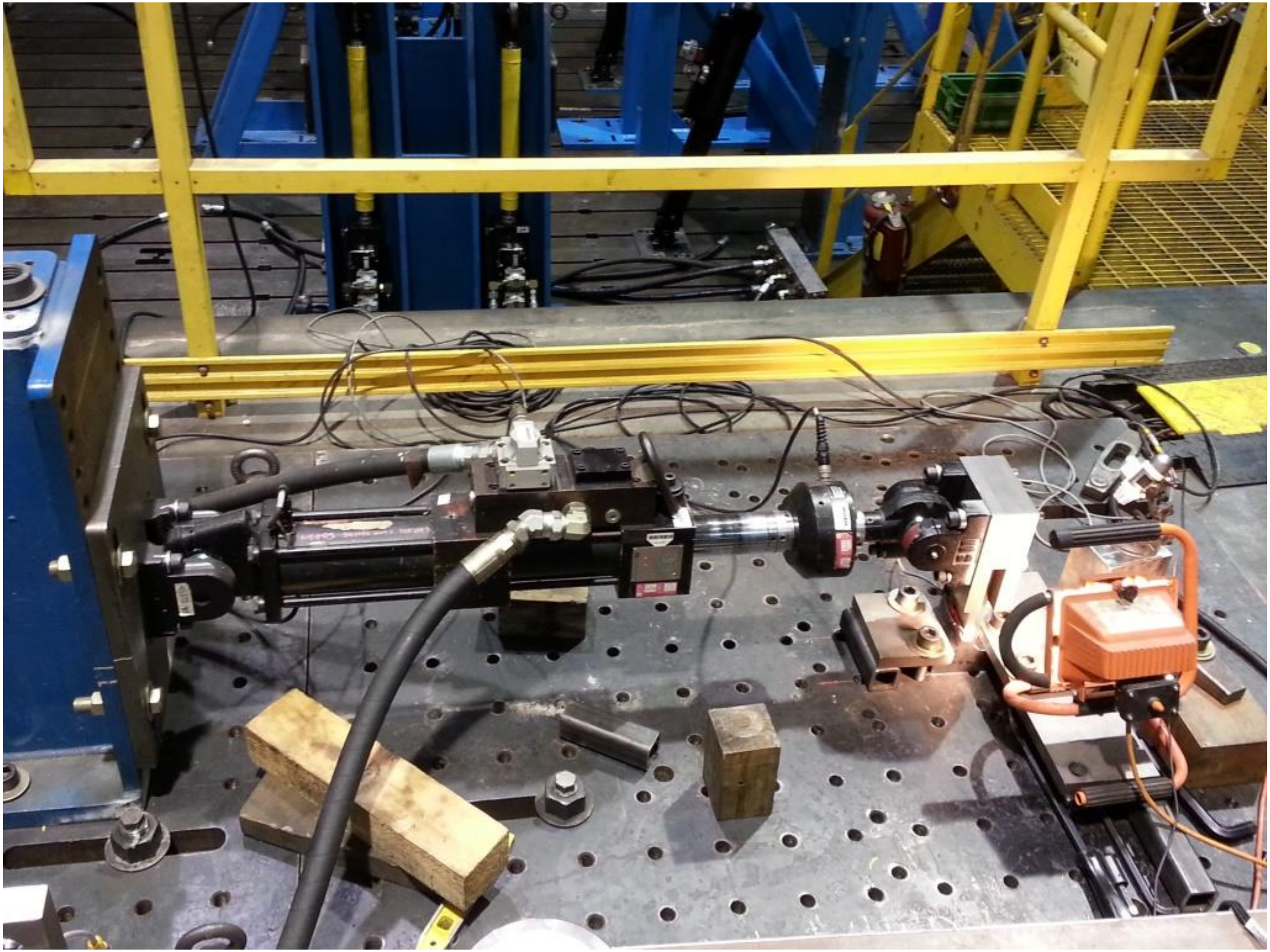






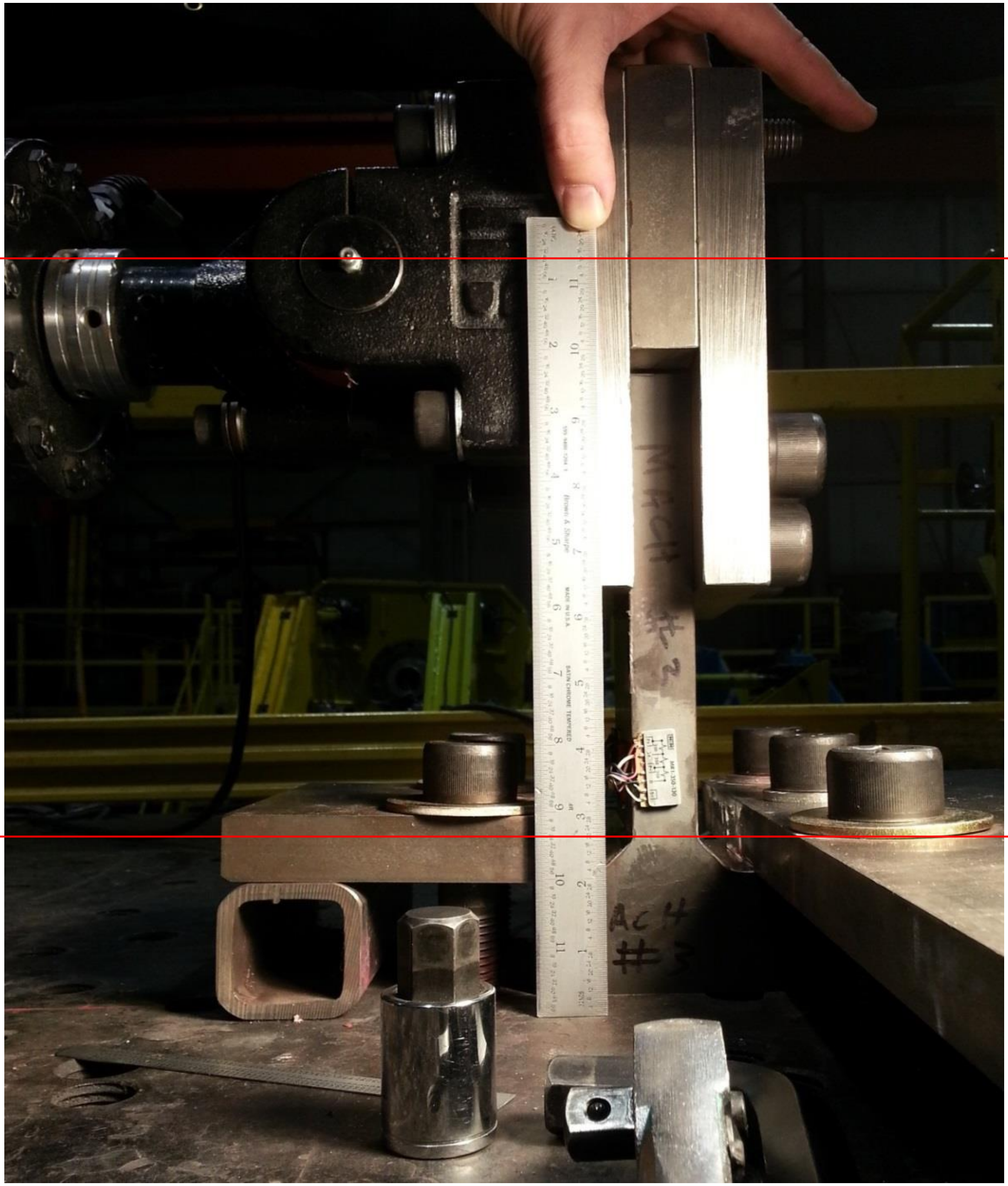
Total Fatigue Life: Crack Initiation and Crack Propagation Analysis

Specimen in Test Fixture



Total Fatigue Life: Crack Initiation and Crack Propagation Analysis

Specimen in Test Fixture/ for FEM Boundary Conditions



222.25mm
From Applied
Load Line to
Radius

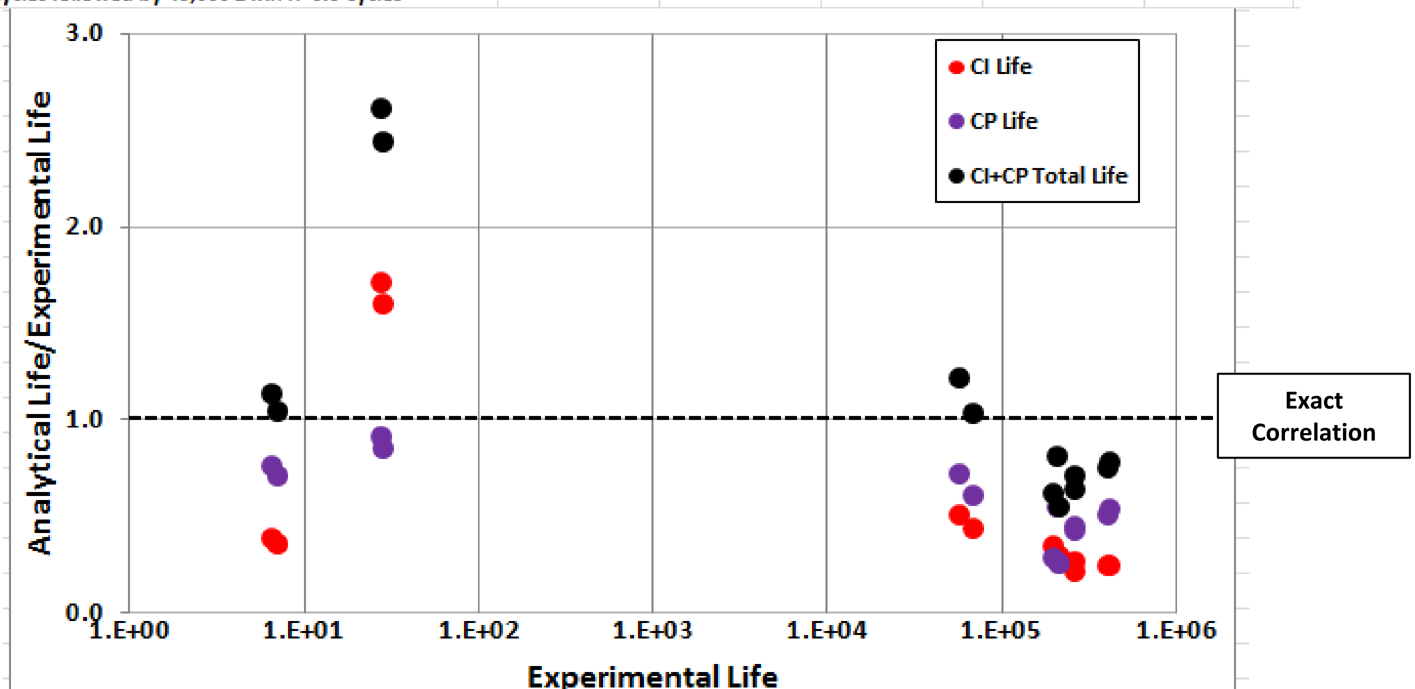
Total Fatigue Life: Crack Initiation and Crack Propagation Analysis

Analytical/Experimental Results: Local Strain CI + G. Glinka CP Analysis - 1

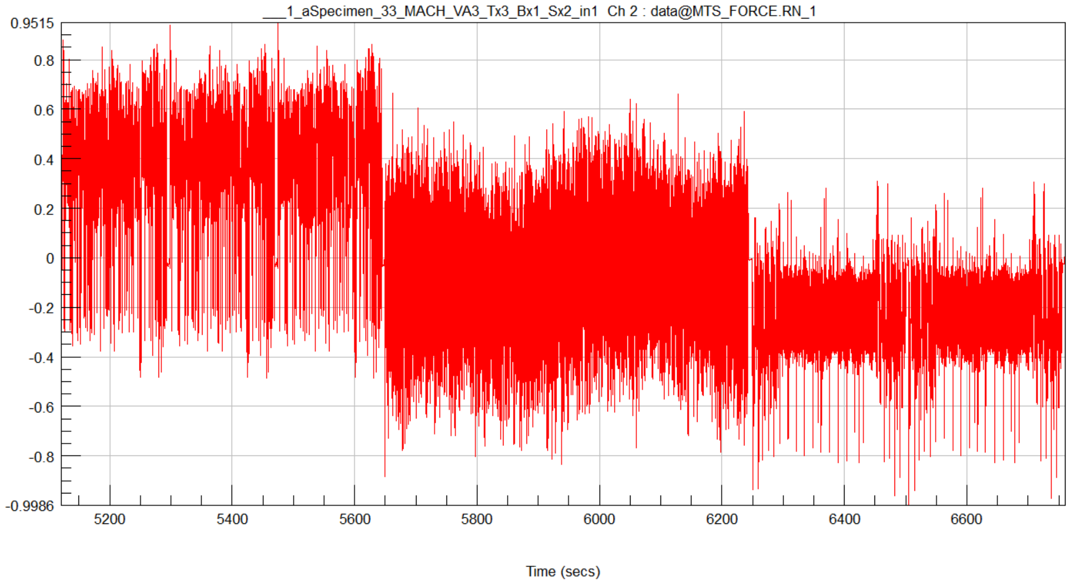
Specimen Number	Test Load Kn	Test R Ratio Dimensionless	Max Stress Level Mpa	Max Strain Level ue	Setup Cycle R Ratio Dimensionless	Test Life (TL) Cycle Counter Cycles or Blocks	Predicted CI Life Cycles or Blocks	Predicted CP Life Cycles or Blocks	Predicted CI+CP Life Cycles or Blocks	CI+CP Life/ Test Life (TL) Dimensionless
22	24	0.3	870.44	4150	0.0	266,012	68,750	117,374	186,124	0.70
25	24	0.3	870.44	4150	0.3	218,671	62,430	54,606	117,036	0.54
35	24	0.3	870.44	4150	0.3	200,464	68,180	54,753	122,786	0.61
19	24	0.1	870.44	4150	0.1	58,481	29,360	41,354	70,714	1.21
23	24	0.1	870.44	4150	0.1	70,011	29,710	41,920	71,630	1.02
20	18	0.1	652.83	3113	0.1	411,745	98,750	205,590	304,340	0.74
24	18	0.1	652.83	3113	0.0	424,431	101,900	225,421	327,321	0.77
26	10.8	-1.0	391.70	1868	None	214,765	57,030	115,000	172,030	0.80
27	10.8	-1.0	391.70	1868	None	271,951	56,870	115,000	171,870	0.63
29	24	*Block: 0.1/.5	870.44	4150	0.1	7.2	2.5	5.0	7.5	1.04
30	24	*Block: 0.1/.5	870.44	4150	0.1	6.7	2.5	5.0	7.6	1.13
32	24	Variable Amplitude	870.44	4150	None	28.0	47.5	25.3	72.9	2.60
33	24	Variable Amplitude	870.44	4150	None	29.0	46.1	24.3	70.5	2.43

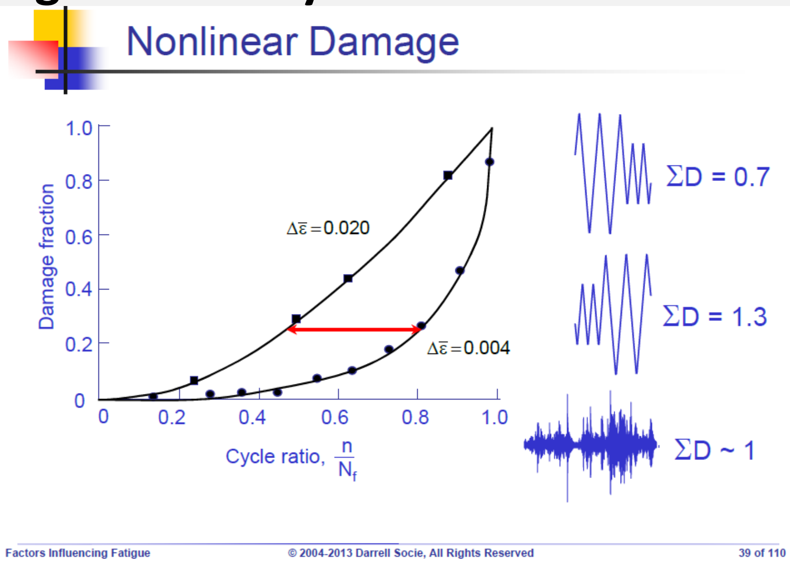
Note: *5,000 24Kn R=0.1 Cycles followed by 40,000 24Kn R=0.5 Cycles

CI+CP TL	CI TL	CP TL
0.70	0.26	0.44
0.54	0.29	0.25
0.61	0.34	0.27
1.21	0.50	0.71
1.02	0.42	0.60
0.74	0.24	0.50
0.77	0.24	0.53
0.80	0.27	0.54
0.63	0.21	0.42
1.04	0.34	0.70
1.13	0.38	0.75
2.60	1.70	0.90
2.43	1.59	0.84



Total Fatigue Life: Crack Initiation and Crack Propagation Analysis





Ref: SAE AE14, Multiaxial Fatigue Analysis and Experiments, "A Summary and Interpretation of the Society of Automotive Engineers' Biaxial Testing Program (1989), Chapter 1, Page 4, Author Darrell Socie

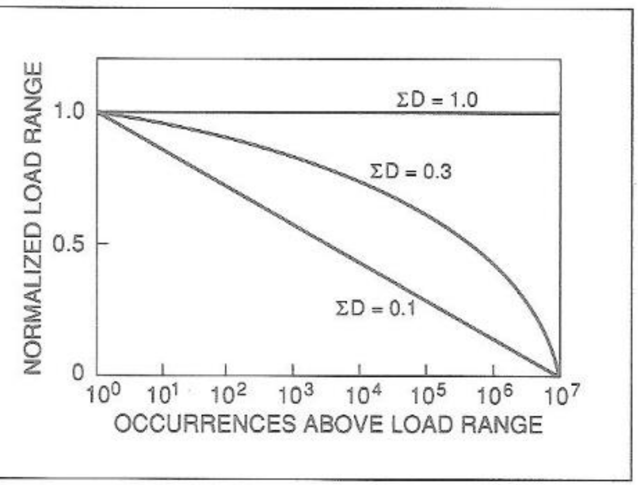
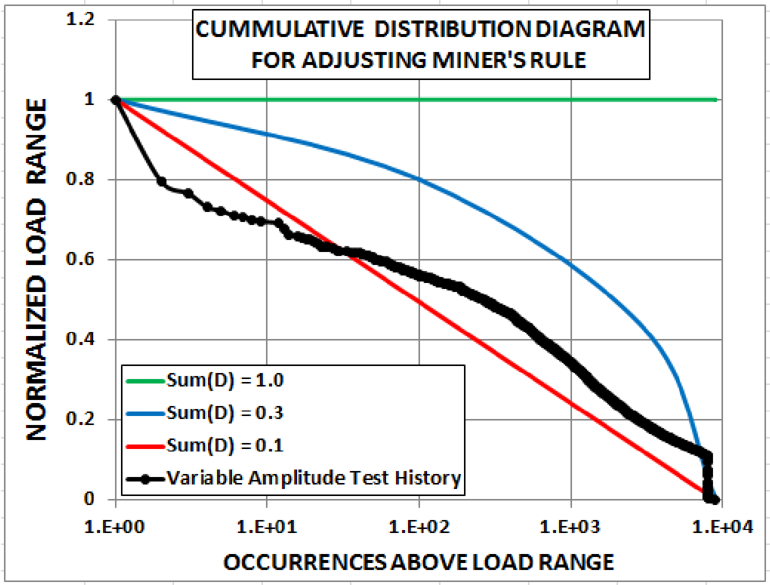


Fig. 4 Cumulative distribution diagram for adjusting Miner's Rule.



Based on the plot in the lower right corner above, should the T-Bar crack initiation Sum(D) = 0.1 (rather then 1.0) for the variable amplitude test history? If so, the current crack initiation predictions are of the magnitude needed to predict a total fatigue life (crack initiation + crack propagation) approximately equal to the experimental total fatigue life.

Total Fatigue Life: Crack Initiation and Crack Propagation Analysis

Analytical/Experimental Results – Local Strain CI + G. Glinka CP Analysis - 2

Specimen Number	Test Load Kn	Test R Ratio Dimensionless	Max Stress Level Mpa	Max Strain Level ue	Setup Cycle R Ratio Dimensionless	Test Life (TL) Cycle Counter Cycles or Blocks	Predicted CI Life Cycles or Blocks	Predicted CP Life Cycles or Blocks	Predicted CI+CP Life Cycles or Blocks	CI+CP Life/ Test Life (TL) Dimensionless
22	24	0.3	870.44	4150	0.0	266,012	68,750	117,374	186,124	0.70
25	24	0.3	870.44	4150	0.3	218,671	62,430	54,606	117,036	0.54
35	24	0.3	870.44	4150	0.3	200,464	68,180	54,753	122,786	0.61
19	24	0.1	870.44	4150	0.1	58,481	29,360	41,354	70,714	1.21
23	24	0.1	870.44	4150	0.1	70,011	29,710	41,920	71,630	1.02
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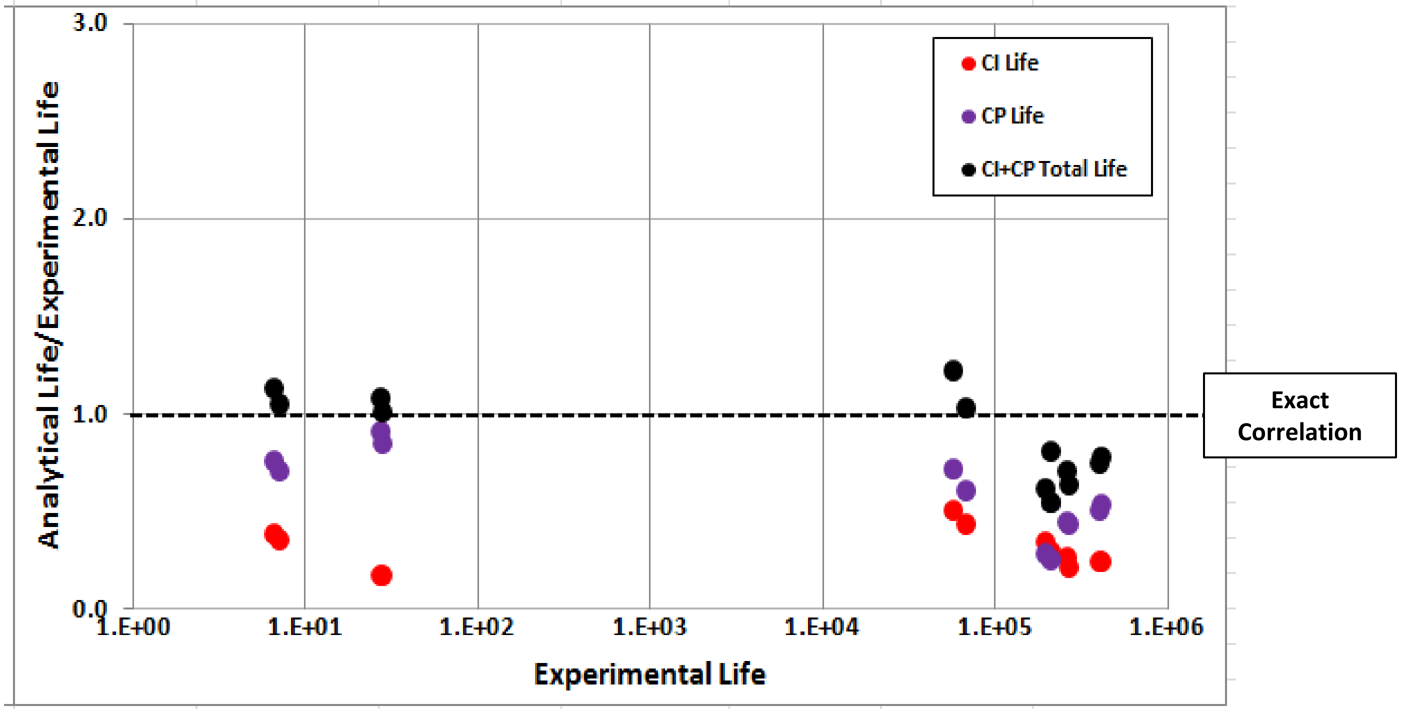
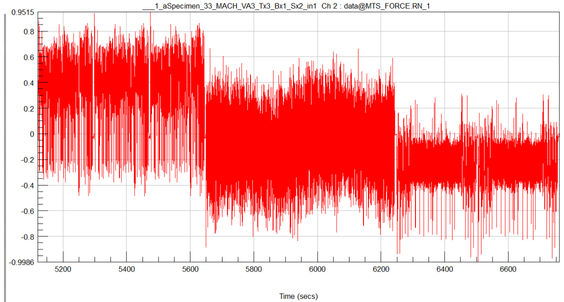
24	18	0.1	652.83	3113	0.0	424,431	101,900	225,421	327,321	0.77
26	10.8	-1.0	391.70	1868	None	214,765	57,030	115,000	172,030	0.80
27	10.8	-1.0	391.70	1868	None	271,951	56,870	115,000	171,870	0.63
29	24	*Block: 0.1/.5	870.44	4150	0.1	7.2	2.5	5.0	7.5	1.04
30	24	*Block: 0.1/.5	870.44	4150	0.1	6.7	2.5	5.0	7.6	1.13
32	24	Variable Amplitude	870.44	4150	None	28.0	4.8	25.3	30.1	1.07
33	24	Variable Amplitude	870.44	4150	None	29.0	4.8	24.3	29.1	1.00

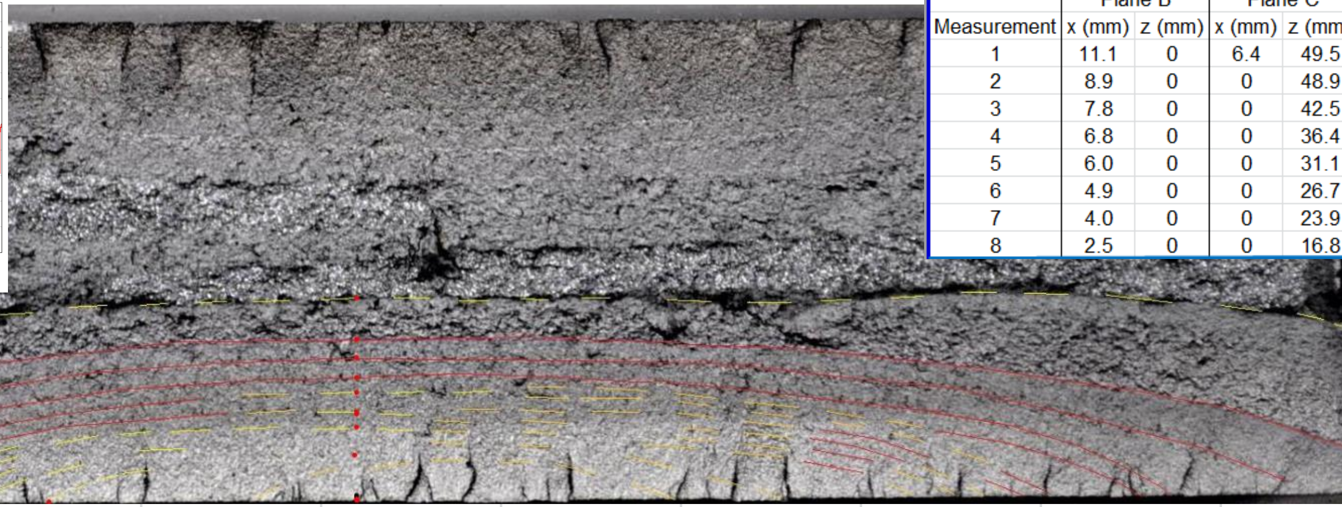
Note: *5,000 24Kn R=0.1 Cycles followed by 40,000 24Kn R=0.5 Cycles

CI+CP TL	CI TL	CP TL
0.70	0.26	0.44
0.54	0.29	0.25
0.61	0.34	0.27
1.21	0.50	0.71
1.02	0.42	0.60
0.74	0.24	0.50
0.77	0.24	0.53
0.80	0.27	0.54
0.63	0.21	0.42
1.04	0.34	0.70
1.13	0.38	0.75
1.07	0.17	0.90
1.00	0.16	0.84



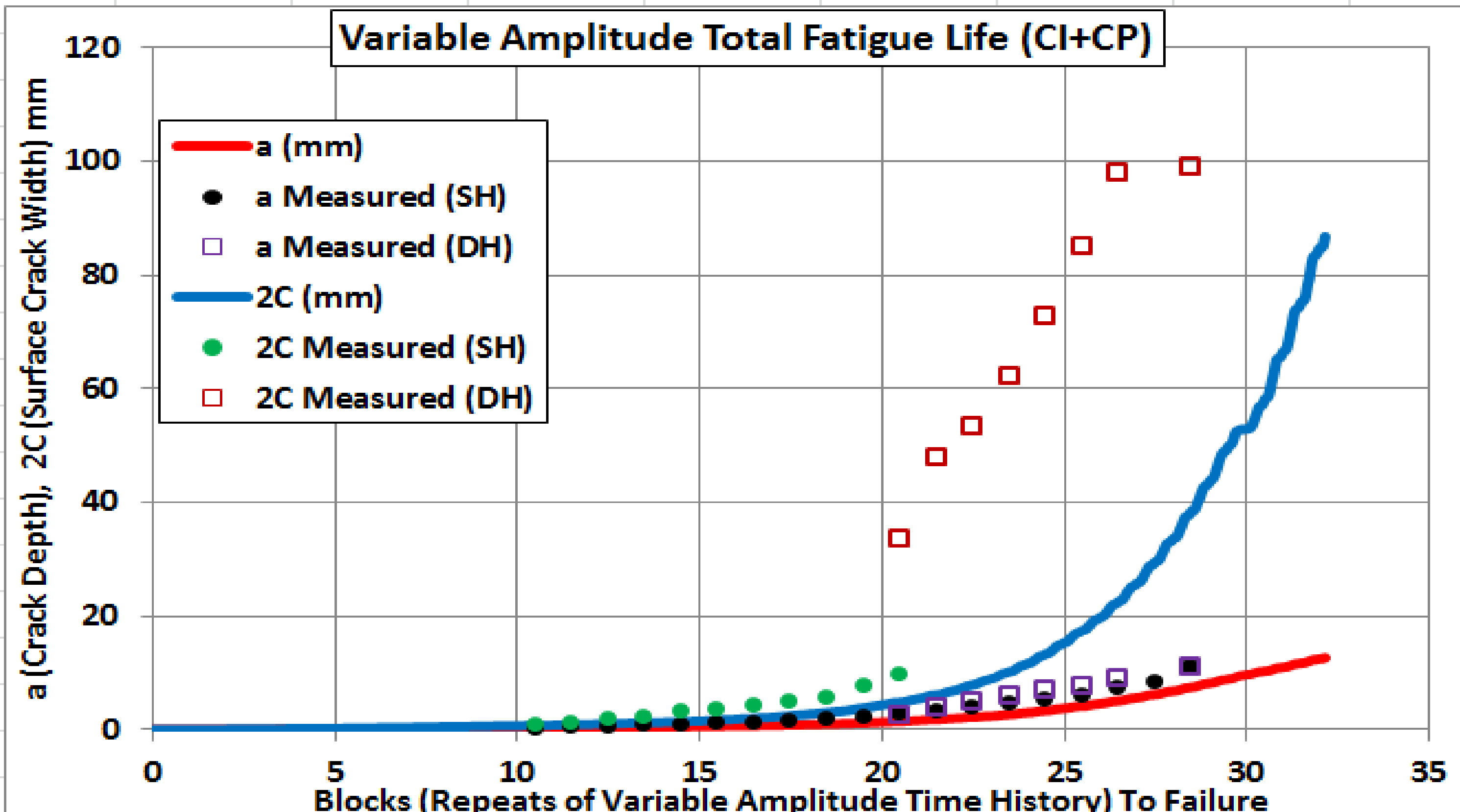
Total Fatigue Life: Crack Initiation and Crack Propagation



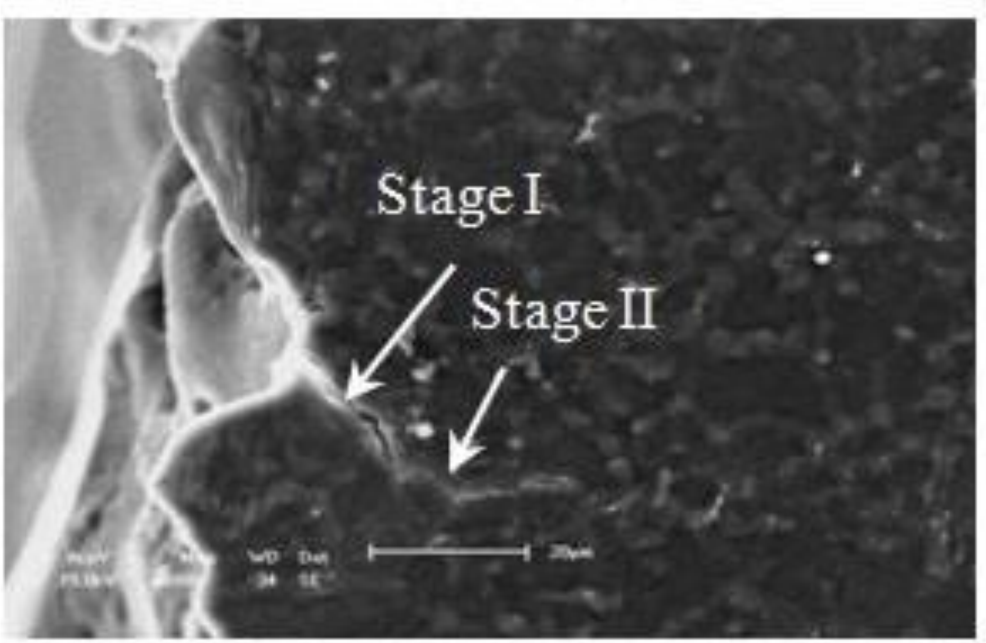


Lambda Technologies				
FRACTURE SURFACE READING				
	Plane B		Plane C	
Measurement	x (mm)	z (mm)	x (mm)	z (mm)
1	11.1	0	6.4	49.5
2	8.9	0	0	48.9
3	7.8	0	0	42.5
4	6.8	0	0	36.4
5	6.0	0	0	31.1
6	4.9	0	0	26.7
7	4.0	0	0	23.9
8	2.5	0	0	16.8

Mississippi State (Stephen J. Horstemeyer)		
Starting from Initiation		By T. Cordes
Edge of Sample in µm	Into Mat'l Blocks in µm	Blocks Re-Referenced From Last Striation
372.34	244.05	10.5
239.56	266.8	11.5
268.88	109.91	12.5
256.46	130.3	13.5
411.59	142.71	14.5
308.17	153.05	15.5
332.99	200.62	16.5
254.4	210.97	17.5
345.4	409.52	18.5
1027.93	444.72	19.5
1110.63	395.04	20.5
	515.01	21.5
	614.28	22.5
	649.44	23.5
	761.12	24.5
	767.32	25.5
	1207.86	26.5
	1100.32	27.5
	2667.4	28.5
4928.35	**10990.44**	



For All Preceding Analysis:
Define CI and CP (ai = ro*)



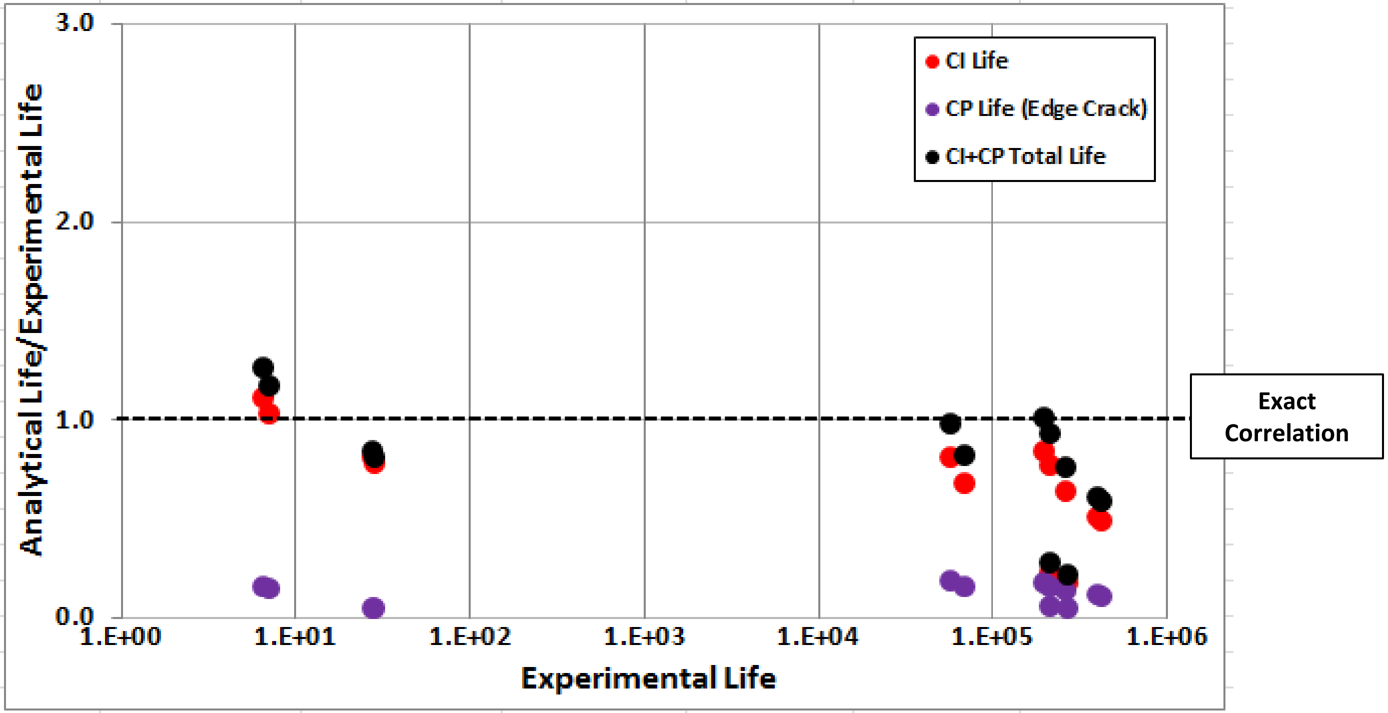
Total Fatigue Life: Crack Initiation and Crack Propagation Analysis

Analytical/Experimental Results – Traditional Analysis

Specimen Number	Test Load Kn	Test R Ratio Dimensionless	Max Stress Level Mpa	Stress Concentration Kt	Setup Cycle R Ratio Dimensionless	Test Life (TL) Cycle Counter Cycles or Blocks	Predicted CI Life Cycles or Blocks	Predicted CP Life Cycles or Blocks	Predicted CI+CP Life Cycles or Blocks	CI+CP Life/ Test Life (TL) Dimensionless
22	24	0.3	488.00	1.784	*	266,012	167,399	33,301	200,700	0.75
25	24	0.3	488.00	1.784	*	218,671	167,399	33,301	200,700	0.92
35	24	0.3	488.00	1.784	*	200,464	167,399	33,301	200,700	1.00
19	24	0.1	488.00	1.784	*	58,481	46,780	10,301	57,081	0.98
23	24	0.1	488.00	1.784	*	70,011	46,780	10,301	57,081	0.82
20	18	0.1	366.00	1.784	*	411,745	204,242	43,961	248,203	0.60
24	18	0.1	366.00	1.784	*	424,431	204,242	43,961	248,203	0.58
26	10.8	-1.0	219.60	1.784	*	214,765	46,788	10,694	57,482	0.27
27	10.8	-1.0	219.60	1.784	*	271,951	46,788	10,694	57,482	0.21
29	24	*Block: 0.1/.5	488.00	1.784	*	7.2	7.4	1.0	8.4	1.16
30	24	*Block: 0.1/.5	488.00	1.784	*	6.7	7.4	1.0	8.4	1.25
32	24	Variable Amplitude	488.00	1.784	*	28.0	22.3	1.0	23.3	0.83
33	24	Variable Amplitude	488.00	1.784	*	29.0	22.3	1.0	23.3	0.80

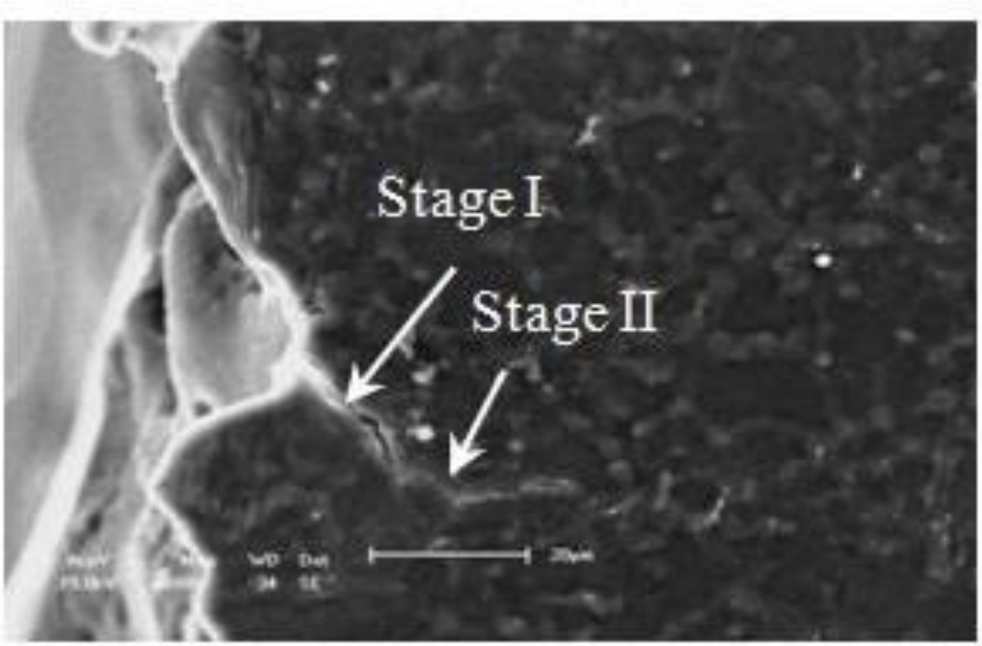
CI+CP TL	CI TL	CP TL (Edge Crack)
0.75	0.63	0.13
0.92	0.77	0.15
1.00	0.84	0.17
0.98	0.80	0.18
0.82	0.67	0.15
0.60	0.50	0.11
0.58	0.48	0.10
0.27	0.22	0.05
0.21	0.17	0.04
1.16	1.02	0.14
1.25	1.10	0.15
0.83	0.80	0.04
0.80	0.77	0.03

Note: *5,000 24Kn R=0.1 Cycles followed by 40,000 24Kn R=0.5 Cycles

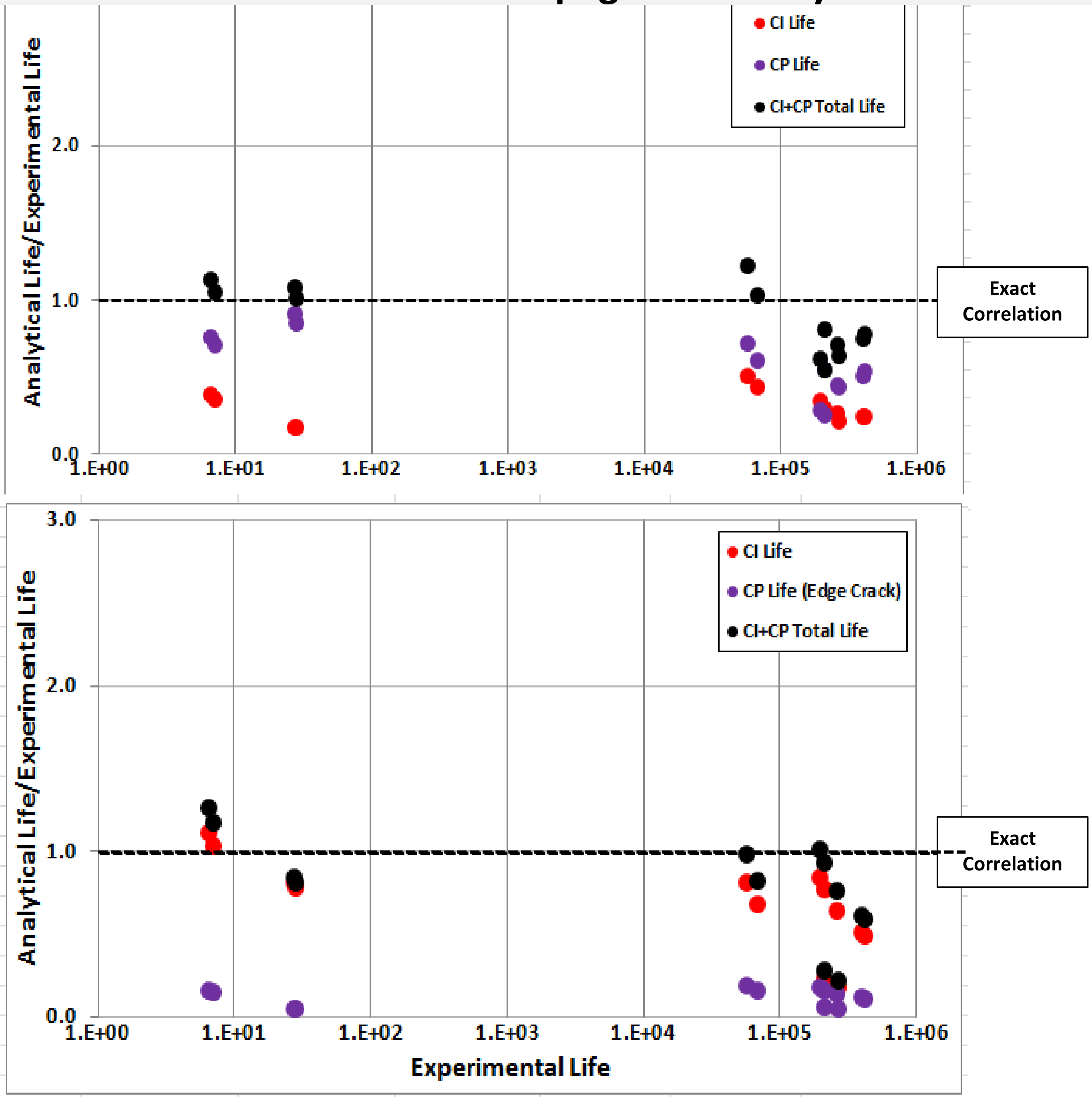


For All Preceding Analysis:
Define CI and CP

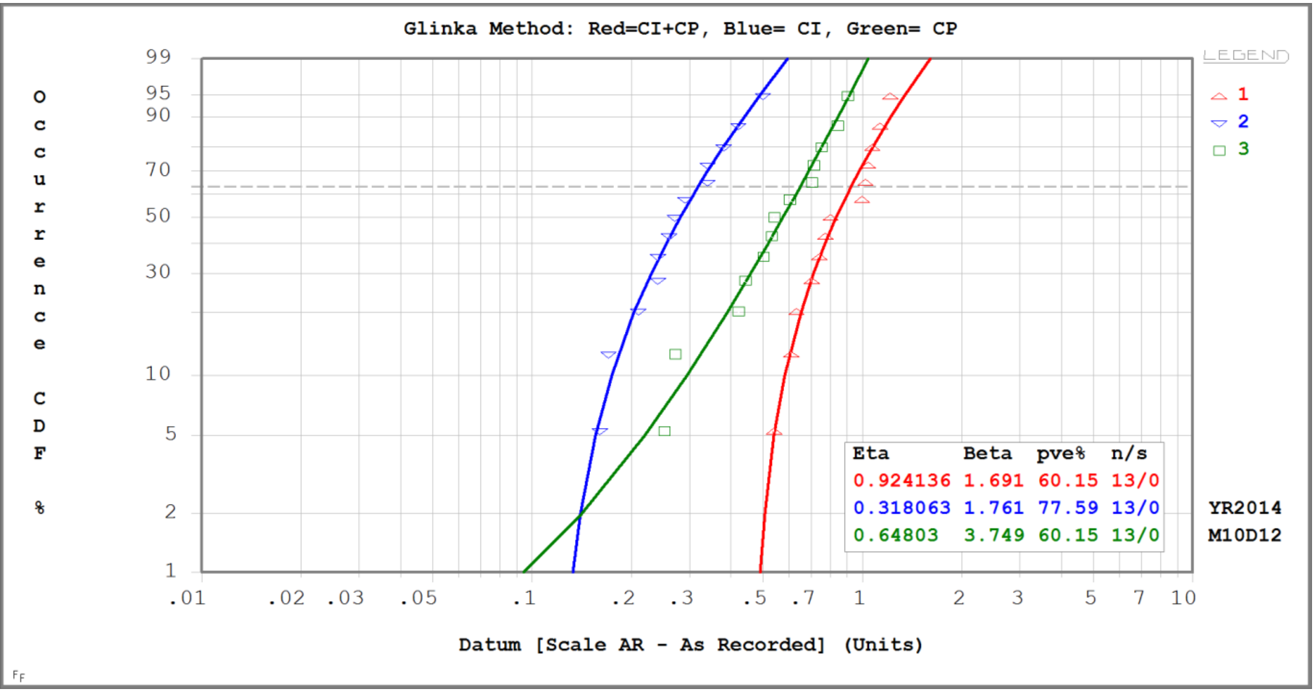
(ai = 0.5mm x 8 mm for 1 to 2 cycles then transitions to an edge crack for the remaining fatigue life)



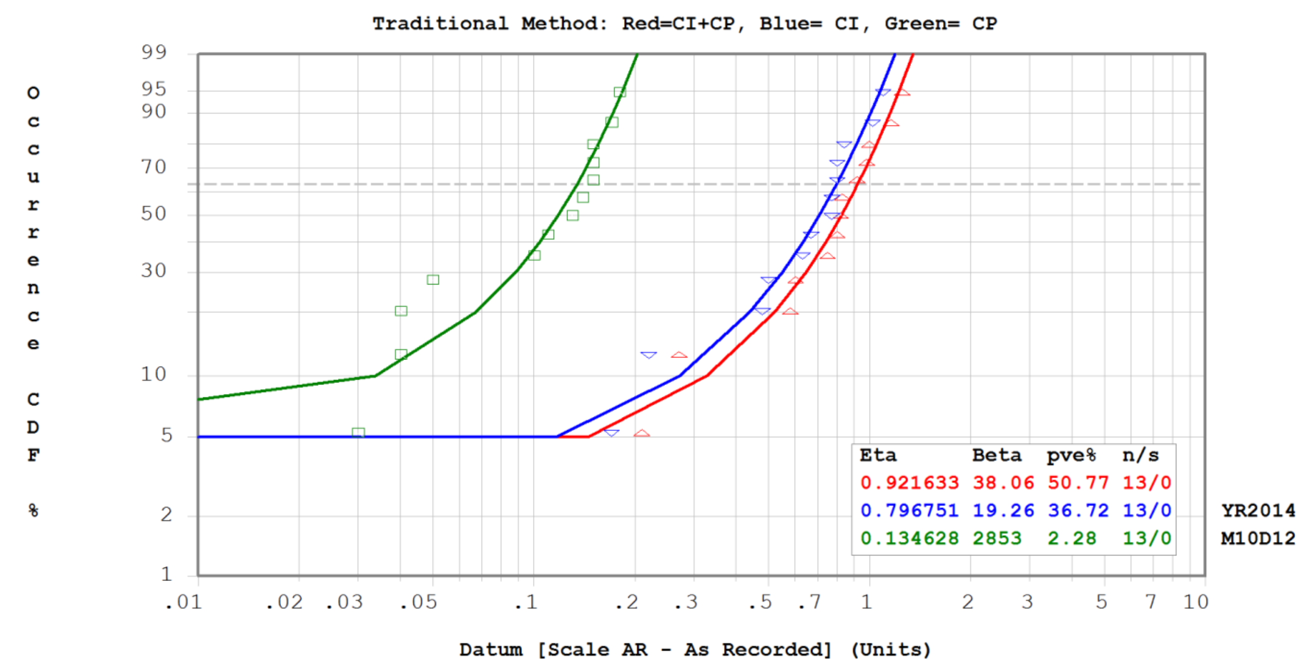
Total Fatigue Life: Crack Initiation + Crack Propagation Analysis



Total Fatigue Life: Crack Initiation and Crack Propagation



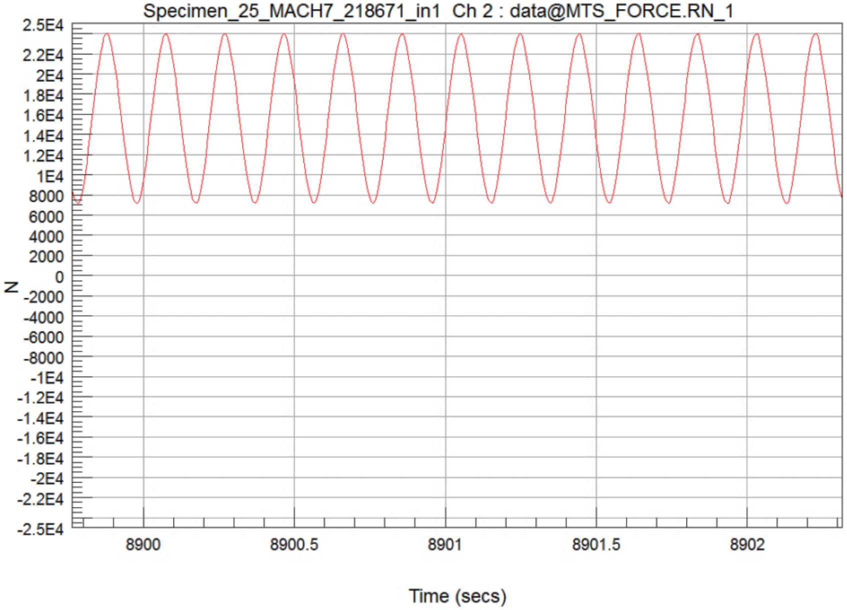
CI+CP TL	CI TL	CP TL
0.70	0.26	0.44
0.54	0.29	0.25
0.61	0.34	0.27
1.21	0.50	0.71
1.02	0.42	0.60
0.74	0.24	0.50
0.77	0.24	0.53
0.80	0.27	0.54
0.63	0.21	0.42
1.04	0.34	0.70
1.13	0.38	0.75
1.07	0.17	0.90
1.00	0.16	0.84



CI+CP TL	CI TL	CP TL (Edge Crack)
0.75	0.63	0.13
0.92	0.77	0.15
1.00	0.84	0.17
0.98	0.80	0.18
0.82	0.67	0.15
0.60	0.50	0.11
0.58	0.48	0.10
0.27	0.22	0.05
0.21	0.17	0.04
1.16	1.02	0.14
1.25	1.10	0.15
0.83	0.80	0.04
0.80	0.77	0.03

Total Fatigue Life: Crack Initiation + Crack Propagation Analysis

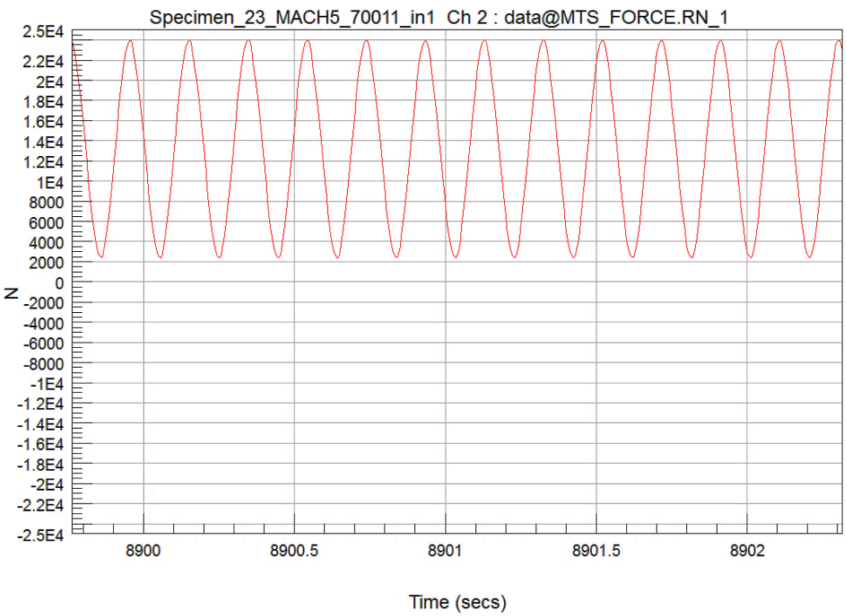
24 kN, R= 0.3



Does the Fracture Surface Agree With Glinka's Changing Aspect Ratio Semi-Elliptical Crack Growth Prediction?
YES

Does the Fracture Surface Agree With The "Traditional" Edge Crack Growth Prediction?
NO

24 kN, R= 0.1

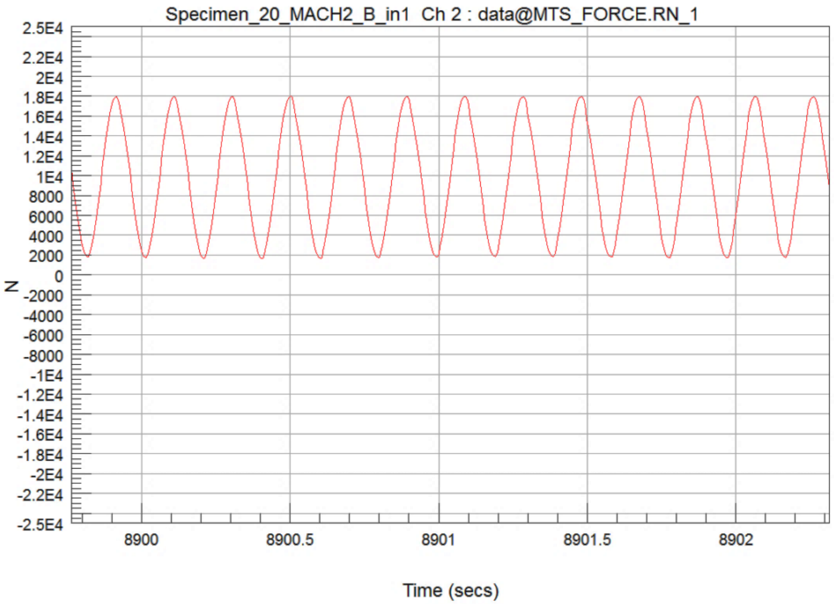


Does the Fracture Surface Agree With Glinka's Changing Aspect Ratio Semi-Elliptical Crack Growth Prediction?
YES

Does the Fracture Surface Agree With The "Traditional" Edge Crack Growth Prediction?
NO

Total Fatigue Life: Crack Initiation + Crack Propagation Analysis

18 kN, R= 0.1

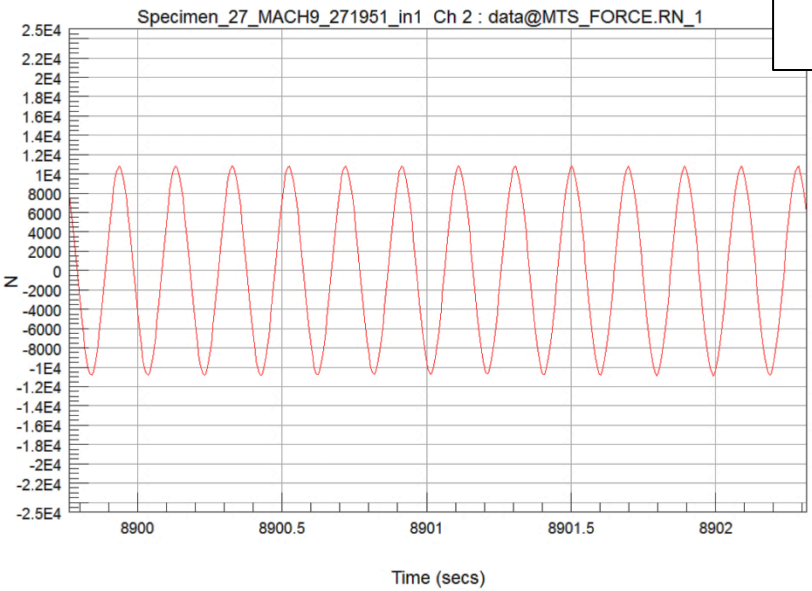


18 kN Lowest Tensile Mean Load - Crack Has Just Progressed Around Free Ends

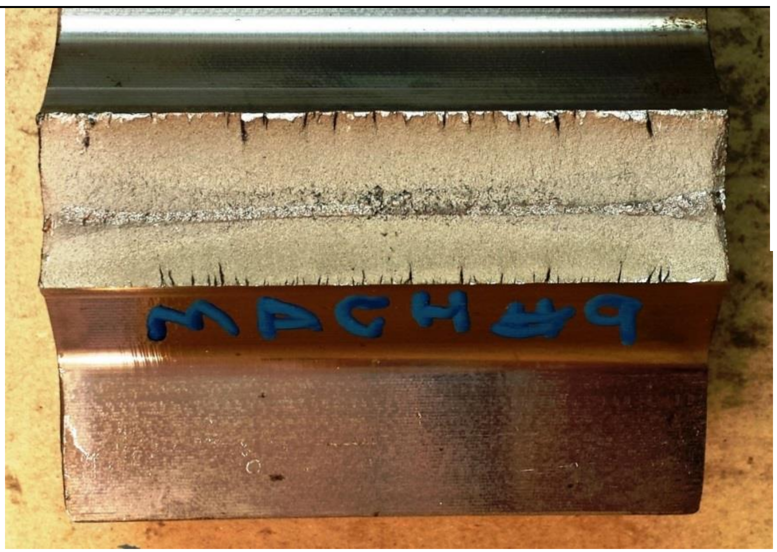
Does the Fracture Surface Agree With Glinka's Changing Aspect Ratio Semi-Elliptical Crack Growth Prediction?
YES

Does the Fracture Surface Agree With The "Traditional" Edge Crack Growth Prediction?
NO

10.8 kN, R= -1



10.8 kN Zero Tensile Mean Load - Crack Progressed Primarily As A Changing Aspect Ratio Semi Elliptical Crack And Then Transitioned To An Edge Crack

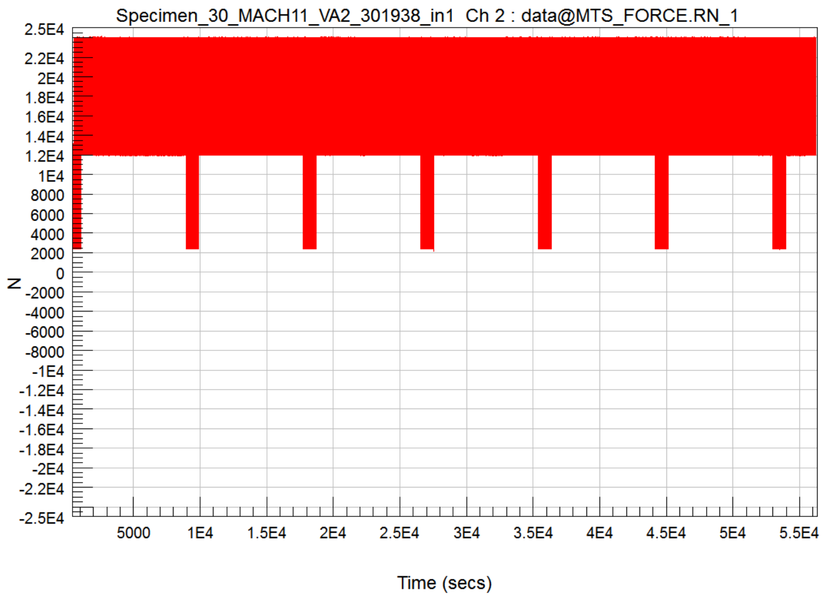


Does the Fracture Surface Agree With Glinka's Changing Aspect Ratio Semi-Elliptical Crack Growth Prediction?
YES

Does the Fracture Surface Agree With The "Traditional" Edge Crack Growth Prediction?
NO

Total Fatigue Life: Crack Initiation + Crack Propagation Analysis

24 kN, VA, Block Loading, R= 0.1 (5k cycles) / R= 0.5 (40k cycles)

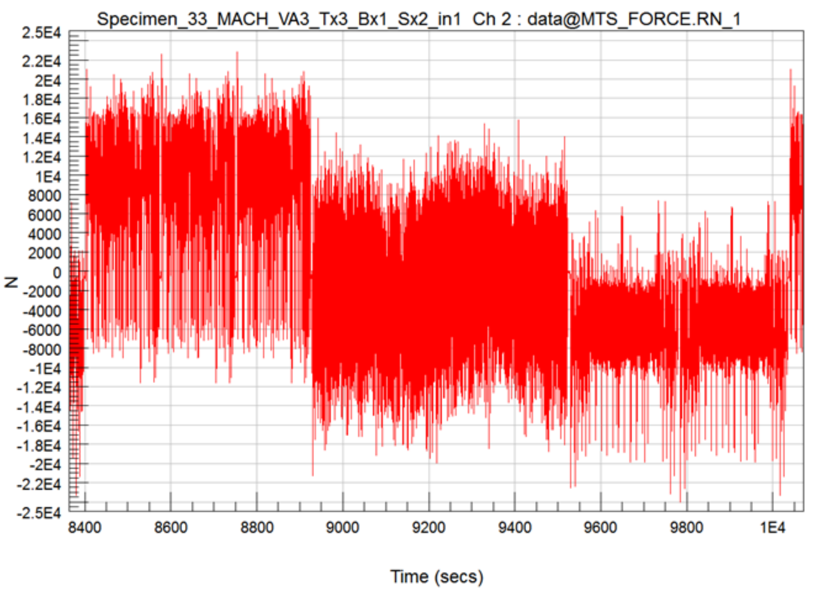


Block Loading: 24 kN/R=0.1 (5k Cycles) Followed By 24 kN/R=0.5 (40k Cycles) Crack Has Just Progressed To Free Ends

Does the Fracture Surface Agree With Glinka's Changing Aspect Ratio Semi-Elliptical Crack Growth Prediction?
YES

Does the Fracture Surface Agree With The "Traditional" Edge Crack Growth Prediction?
NO

24 kN Max / 24 kN Min, VA, Time History Profile (Trans x3, Brkt x1, Susp x2)

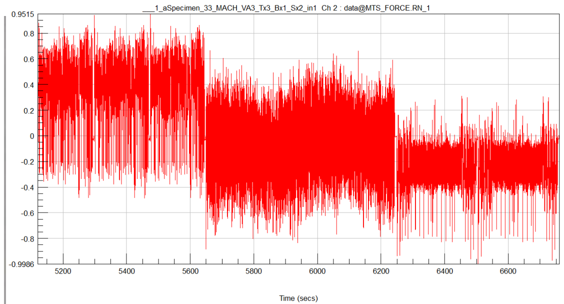


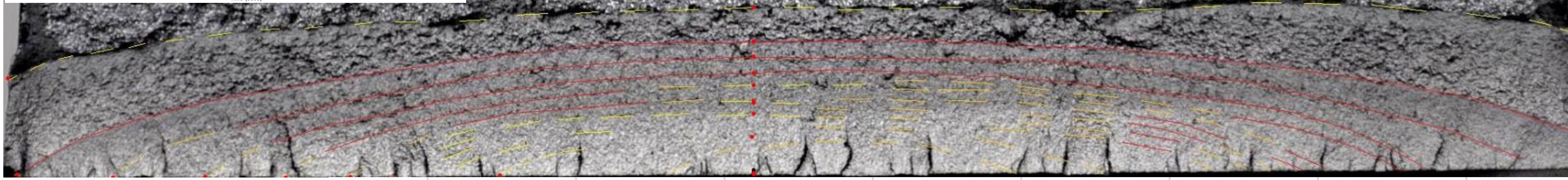
SAE Time History: TransX3_BrktX1-SuspX2 Crack Progressed Primarily As A Changing Aspect Ratio Semi Elliptical Crack And Then Transitioned To An Edge Crack

Does the Fracture Surface Agree With Glinka's Changing Aspect Ratio Semi-Elliptical Crack Growth Prediction?
YES

Does the Fracture Surface Agree With The "Traditional" Edge Crack Growth Prediction?
NO

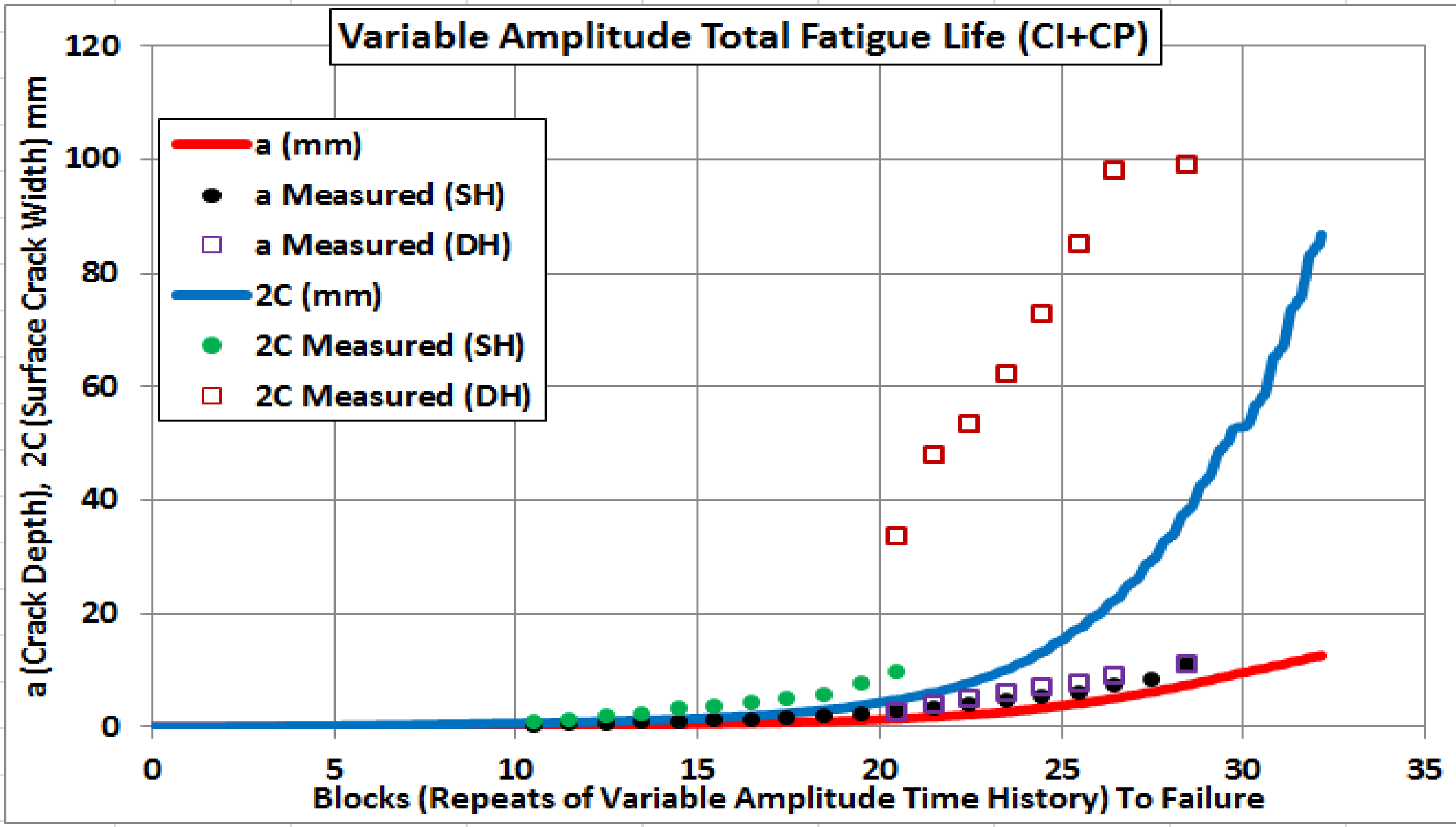
Total Fatigue Life: Crack Initiation and Crack Propagation





Lambda Technologies				
FRACTURE SURFACE READING				
	Plane B		Plane C	
Measurement	x (mm)	z (mm)	x (mm)	z (mm)
1	11.1	0	6.4	49.5
2	8.9	0	0	48.9
3	7.8	0	0	42.5
4	6.8	0	0	36.4
5	6.0	0	0	31.1
6	4.9	0	0	26.7
7	4.0	0	0	23.9
8	2.5	0	0	16.8

Mississippi State (Stephen J. Horstemeyer)		
Starting from Initiation		By T. Cordes
Edge of Sample in µm	**Into Mat'l Blocks in µm**	**Blocks Re-Referenced From Last Striation**
372.34	244.05	10.5
239.56	266.8	11.5
268.88	109.91	12.5
256.46	130.3	13.5
411.59	142.71	14.5
308.17	153.05	15.5
332.99	200.62	16.5
254.4	210.97	17.5
345.4	409.52	18.5
1027.93	444.72	19.5
1110.63	395.04	20.5
	515.01	21.5
	614.28	22.5
	649.44	23.5
	761.12	24.5
	767.32	25.5
	1207.86	26.5
	1100.32	27.5
	2667.4	28.5
4928.35	**10990.44**	



Total Fatigue Life: Crack Initiation and Crack Propagation

No.	Issue	Glinka's Method	Traditional Method
1	Makes LEFM crack propagation predictions when "bulk" mat'ls are elastic	Yes	Yes
2	Makes NLEFM crack propagation predictions when "bulk" mat'ls becomes plastic!!!	Yes	No
3	Utilizes "libraries" of SIF's utilizing the specific elastic stress distribution/state for that geometry	Yes	Yes
4	Utilizes "libraries" of UWF's inputting the LFEM stress distribution (NL?) for a generically defined geometry!!!	Yes	No
5	Calculates the crack aspect ratio change as a two dimensional crack grows thru the thickness!!!	Yes	No
6	When making Total Fatigue Life CI+CP predictions, the CP ai is a defined value	Yes	No - Guess
7	Significant high confidence libraries of crack growth mat'l property fit constants exist for methodolgy	No	No?- A?,P?
8	One mat'l property fit well defined collapsed curve/constants is obtainable from 3 to 5 R ratio data sets	Yes	No?- Walker?
9	Mat'l property R ratio data sets are obtainable by digitizing the appropriate R ratio curves from literature	Yes	Yes
10	When making Total Fatigue Life CI+CP predictions the method uses fundamentally the same s-e tracking math!!!	Yes	No
11	Residual stress distribution input ability for calc. of K(residual) and proper incorporation into crack damage model!!!	Yes	No
12	Doesn't use conventional rainflow counted cycles because they are not proper peak-valley sequence fo CP!!!	Yes	No

The preceding presentation documents conclusively that when Gregory Glinka's *"elegant"* crack growth prediction methodology is linked with it's (consistent physics and mathematics) crack initiation methodology, that total fatigue life predictions are achievable to a degree of accuracy never before considered possible. The linked methodology even defines the cycle by cycle changing crack depth relative to width versus cycles from initiation to failure. This has even been accomplished using A36 steel – one of the most "method challenging" materials.

Thank You

Total Fatigue Life: Crack Initiation and Crack Propagation

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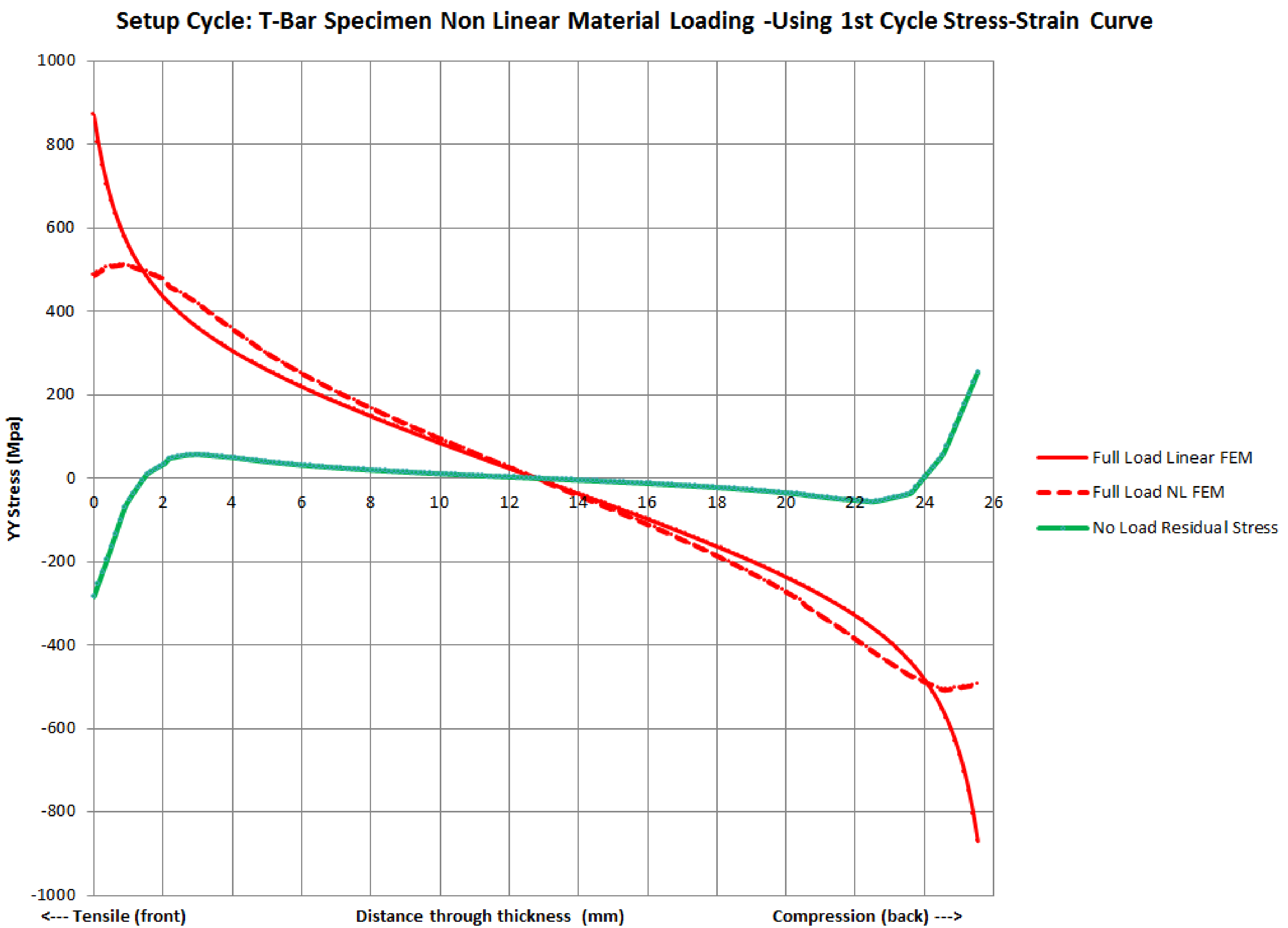
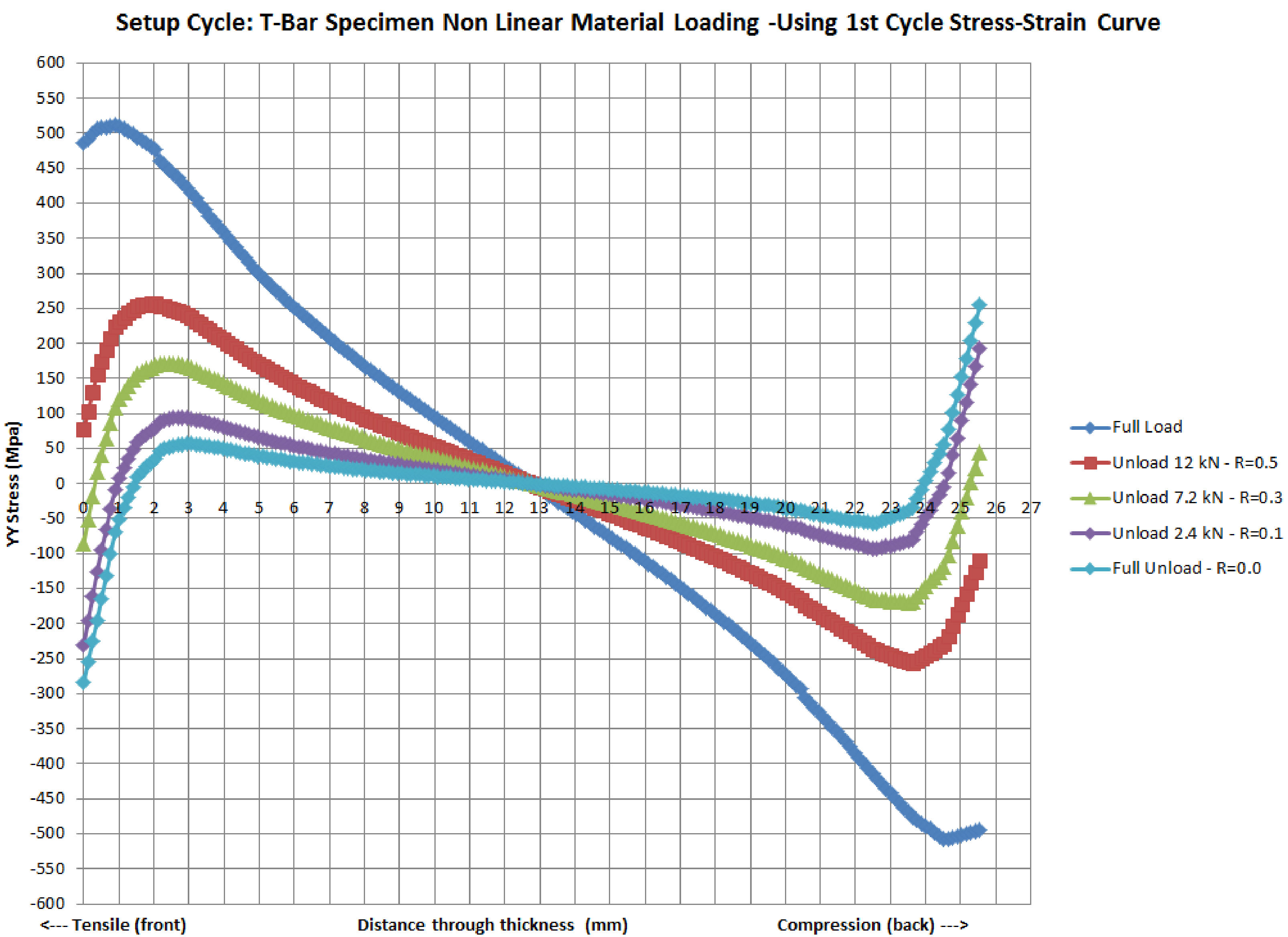
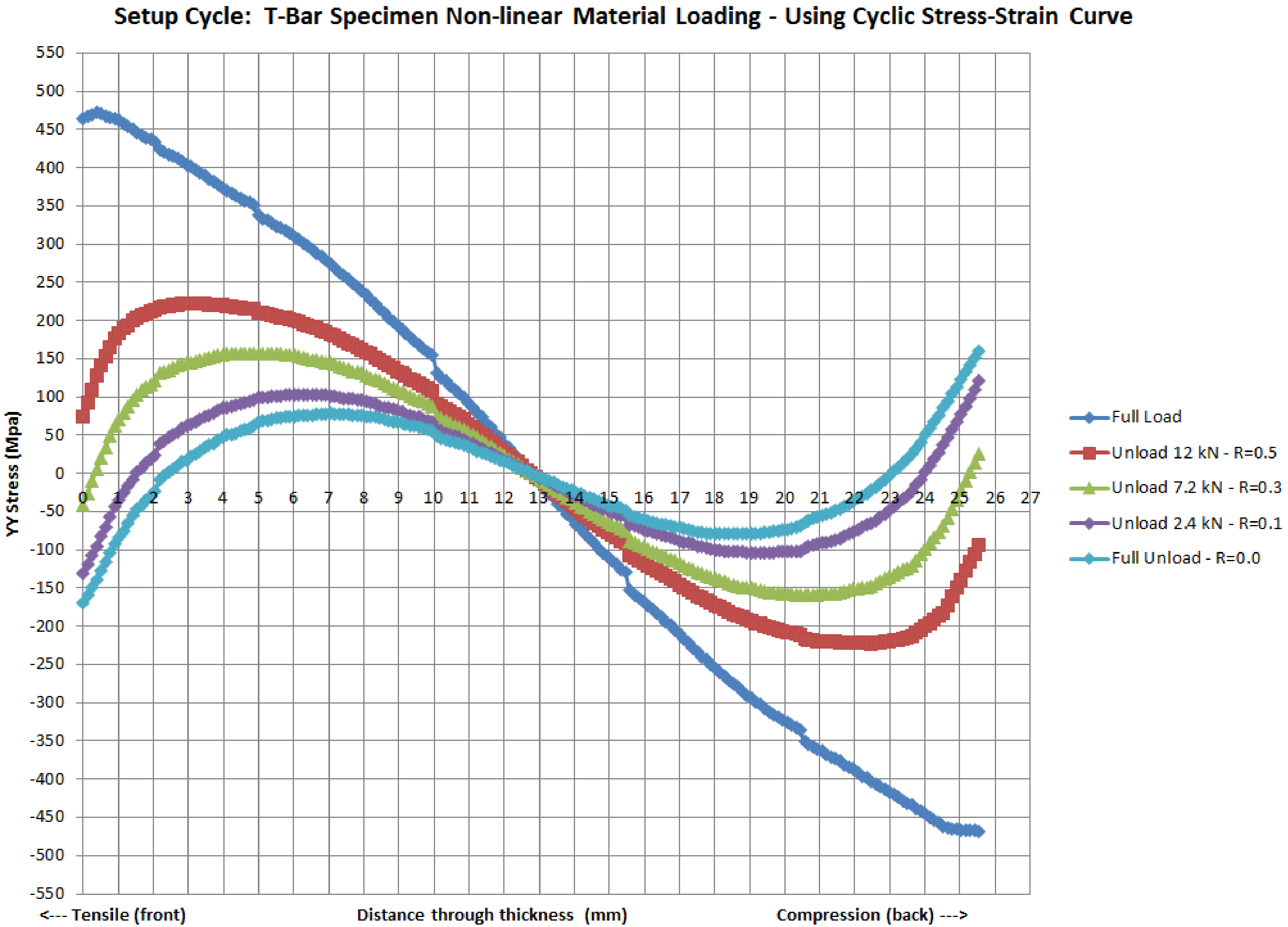
Total Fatigue Life: Crack Initiation + Crack Propagation Analysis





Setup Cycle: T-Bar Specimen Non Linear Material Loading -Using 1st Cycle Stress-Strain Curve
YY Stress (Mpa)
600
550
500
450
400
350
300
250
200
150
100
50
0
-50
-100
-150
-200
-250
-300
-350
-400
-450
-500
-550
-600
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27
<--- Tensile (front)
Distance through thickness (mm)
Compression (back) --->
Full Load
Unload 12 kN - R=0.5
Unload 7.2 kN - R=0.3
Unload 2.4 kN - R=0.1
Full Unload - R=0.0

Total Fatigue Life: Crack Initiation + Crack Propagation Analysis



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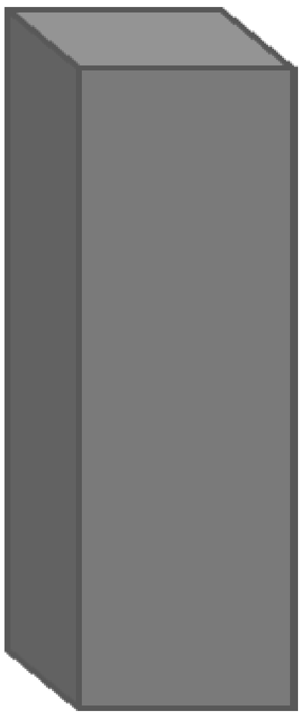
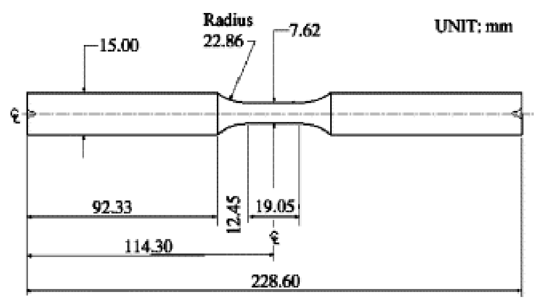
Maintain Exact – Same Steel Pedigree (Material Characterization) Definition/Documentation

Purchased "Enough" 4 A36 20ft HR bars



Microstructure, Chemistry & Hardness Sample



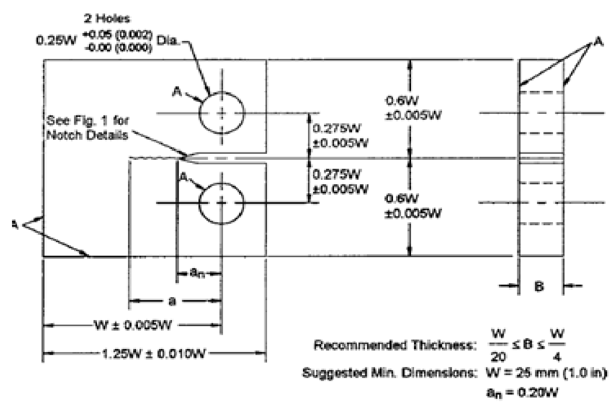
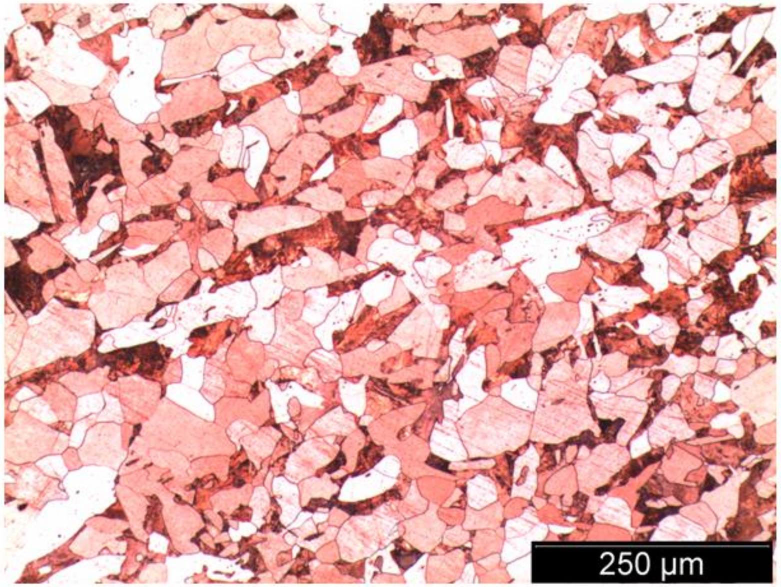


FIG. A1.1 Standard Compact-Tension C(T) Specimen for Fatigue Crack Growth Rate Testing
W=76.2 mm (3 in), B= 19.05 mm (0.75 in)

Total Fatigue Life: Crack Initiation and Crack Propagation Analysis

Steel Microstructure, Hardness, Grain Size and Chemistry

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

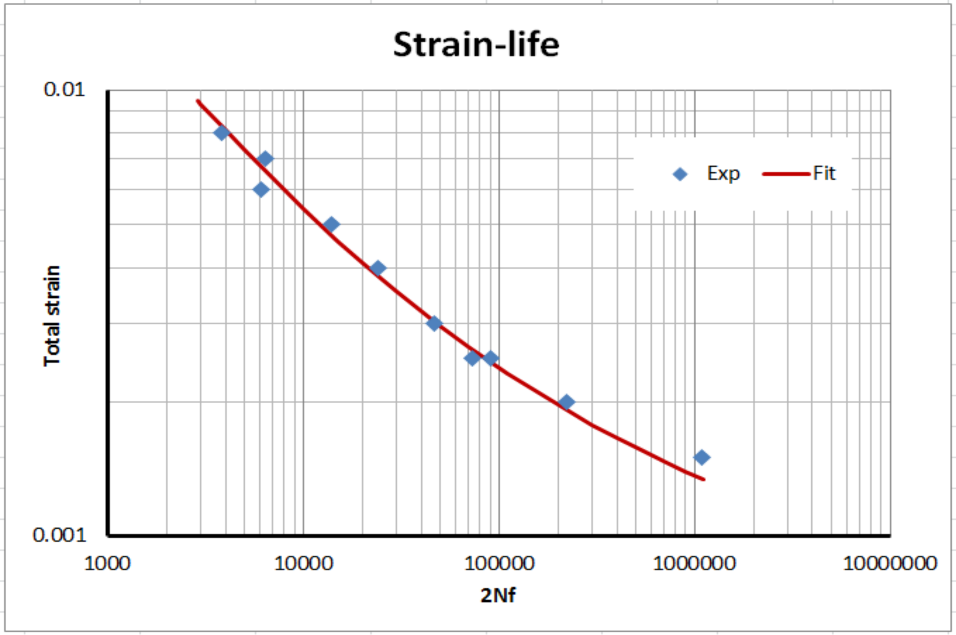


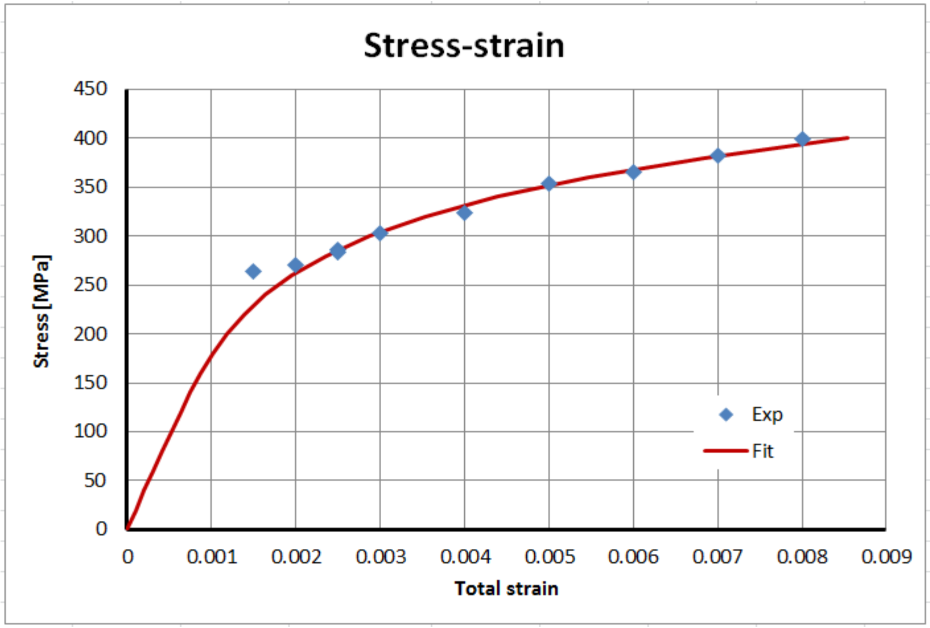
	C165 %	C-LOW %	Mn403.4 %	Si288 %	P177 %	S180 %	Cr_Calc.	Ni341 %	Mo386 %	Cu327 %
Average	0.199	0.212	0.807	0.237	0.012	0.044	0.093	0.100	0.006	0.260
Std. Deviation	0.009	0.0099	0.009	0.003	0.001	0.002	0.000	0.002	0.000	0.004
%RSD	4.60	4.68	1.08	1.17	4.32	5.38	0.48	1.81	5.72	1.45
1 (Yes)	0.189	0.202	0.804	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

Total Fatigue Life: Crack Initiation and Crack Propagation Analysis

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

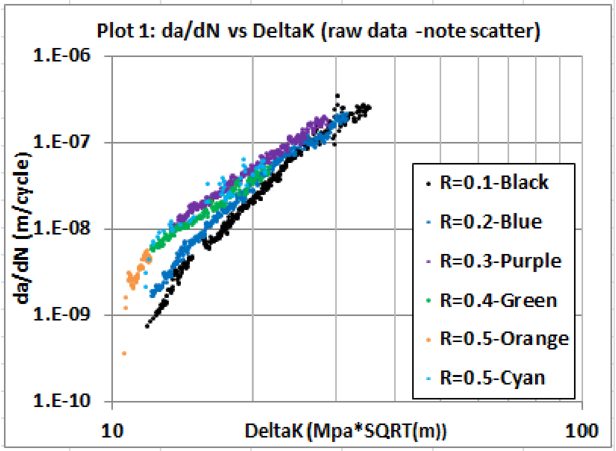


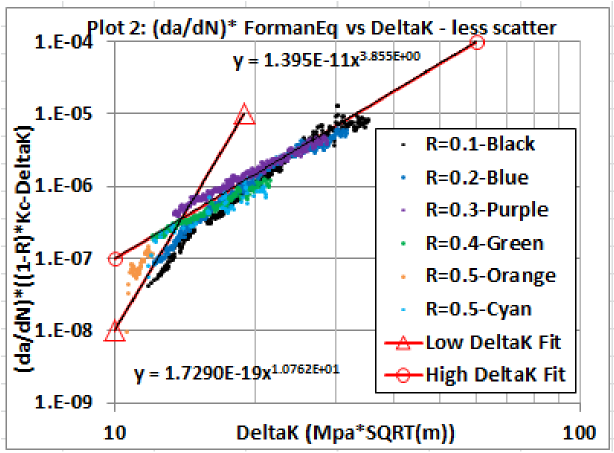


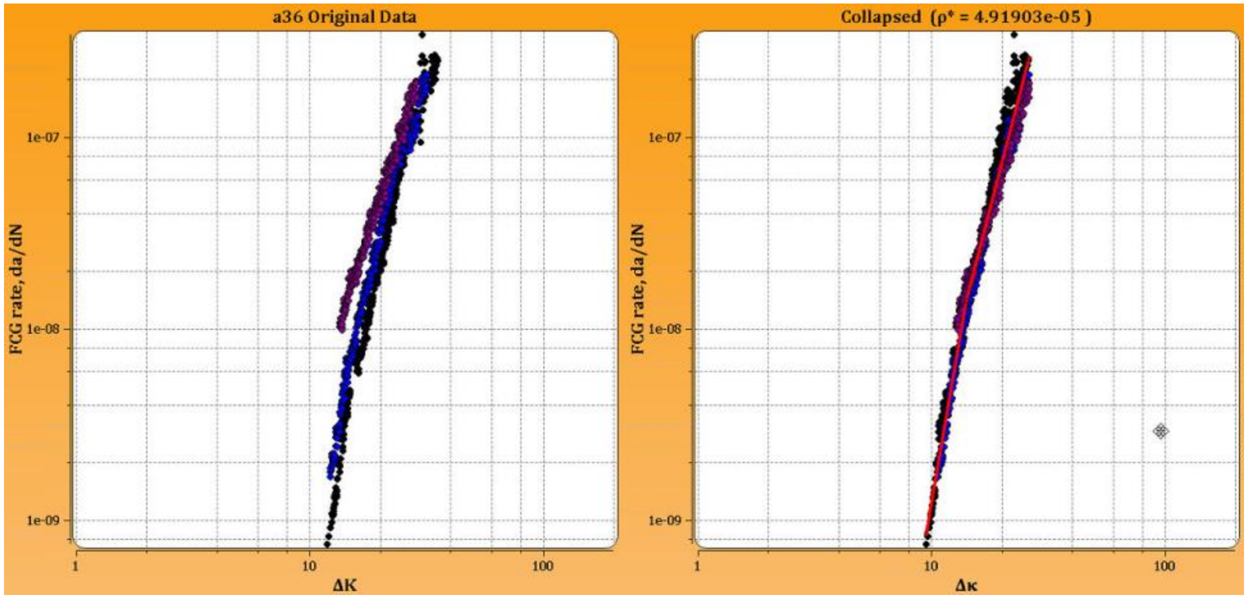
E	Sys	K'	n'	sf'	ef'	b	c
190786	324.12	991.4	0.1799	1025.9	0.7627	-0.1132	-0.5837

Needs Updating

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.

Needs Updating

Total Fatigue Life: Crack Initiation and Crack Propagation

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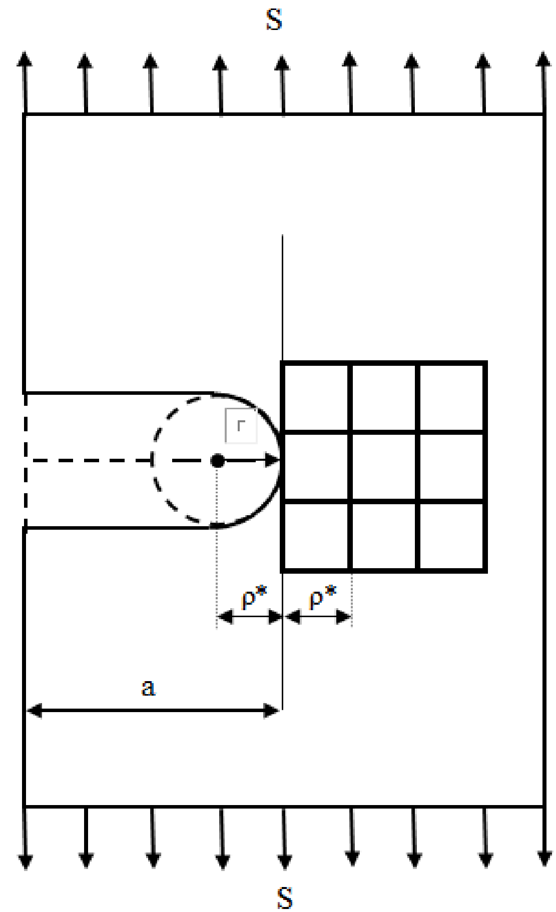
Basics Assumptions

- 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:

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



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)

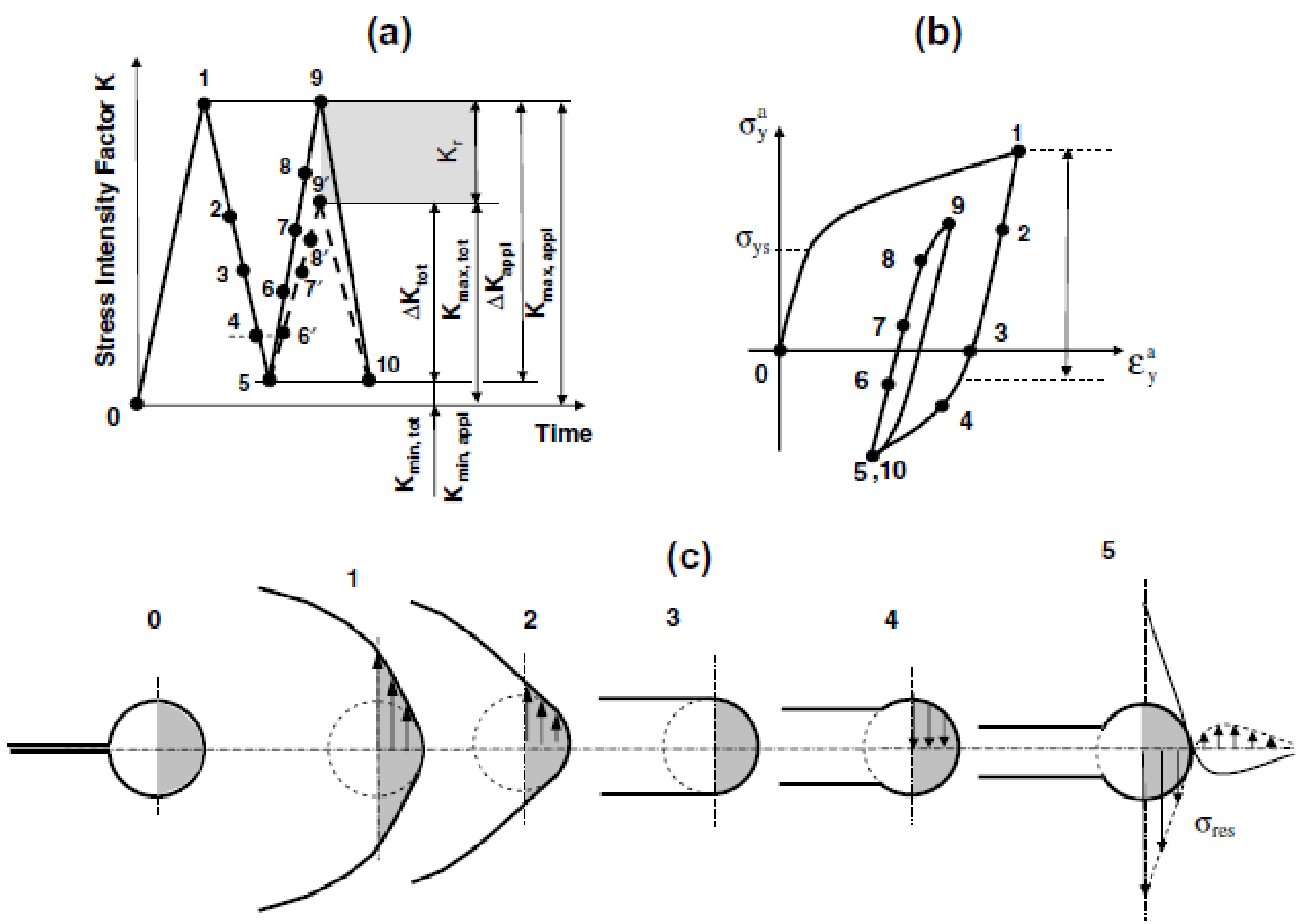


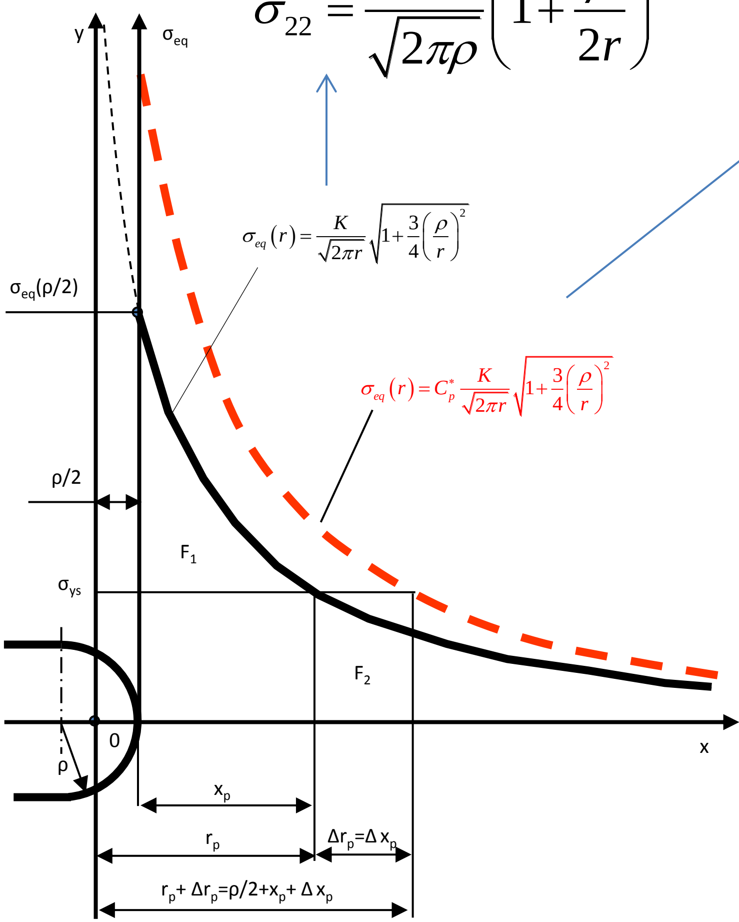
Fig. 1. Schematic crack tip geometry and displacement field, cyclic plastic zone, crack tip stress–strain response and the residual stress distribution: (a) applied load (stress intensity factor) history, (b) qualitative stress–strain response at crack tip, and (c) evolution of the crack opening displacements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

New plastic zone correction C_p

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

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

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



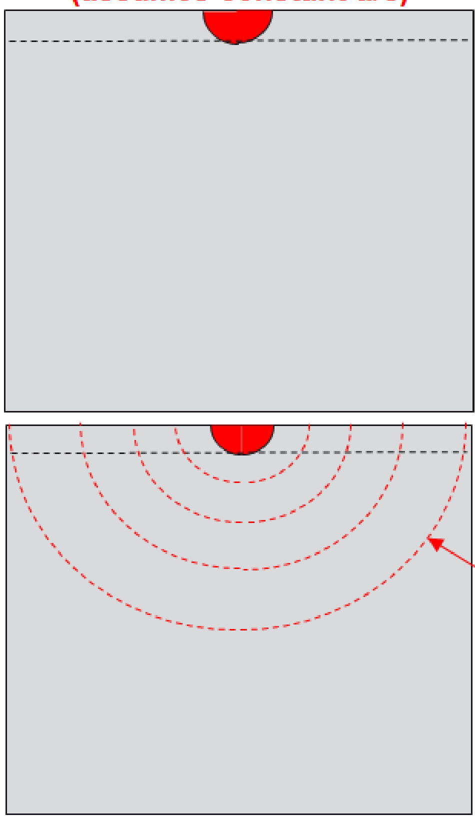
- Elastic stresses ahead of the notch/crack should be redistributed due to the plastic deformations other X_p distance
- Original correction C_p was based on the equivalent stress
- The main idea: the classical plastic zone should be extended by the amount DX_p such that $F_1=F_2$
- Finding F_1 area 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 – Summary of Enhancement Used in the Crack Propagation Analysis

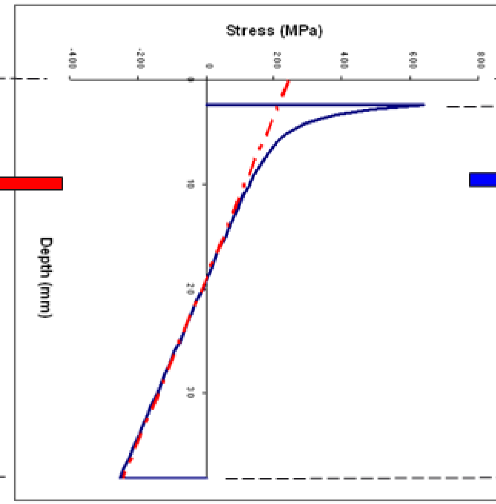
Best to Use Universal Weight Function (UWF) Stress Intensity File (SIF) Capability
(Get a More Representative Stress Intensity Solution Directly From the Actual Geometry FEM Stress Distribution)

Some Other SIF Approaches
(a similar geometry stress intensity factor distribution is picked from a library of solutions)

Un-notched Geometry
(assumes constant a/c)

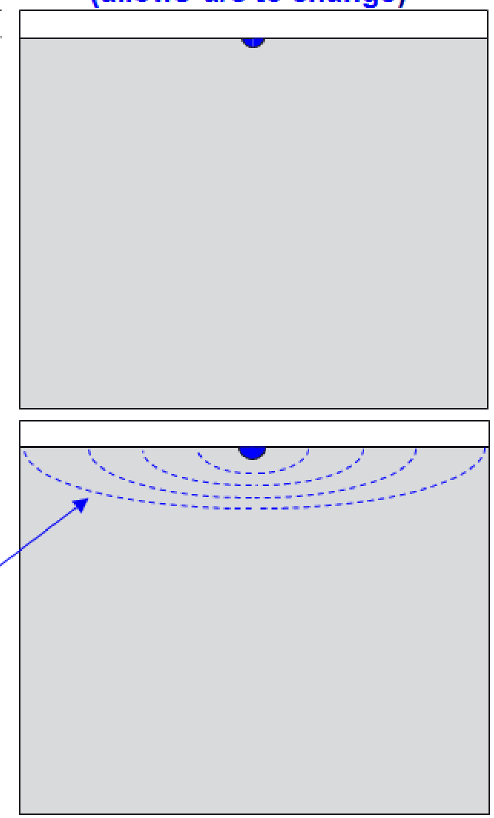


Stress Distribution



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

Notched Geometry
(allows a/c to change)



Note that the crack grows at the same rate on the surface as it does into the depth

Note that the crack grows faster on the surface then it does into the depth

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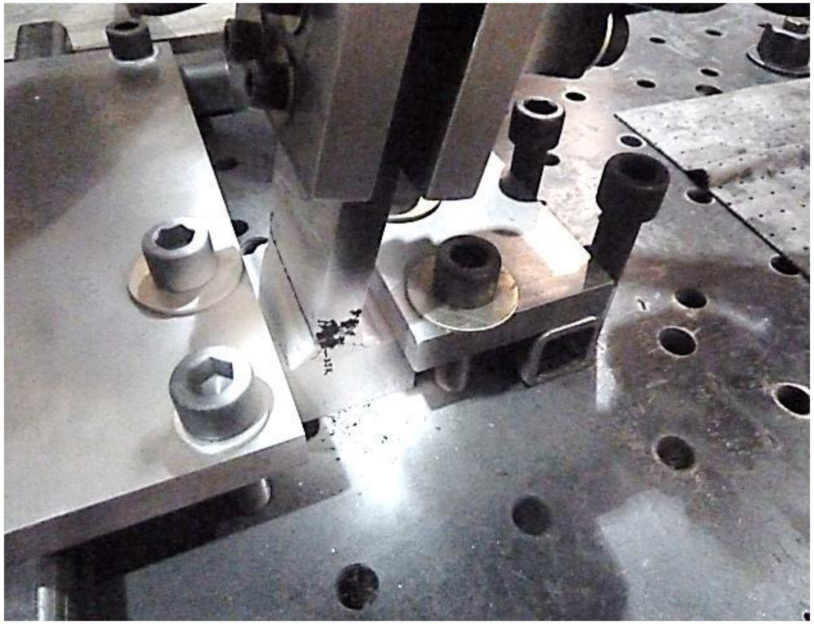
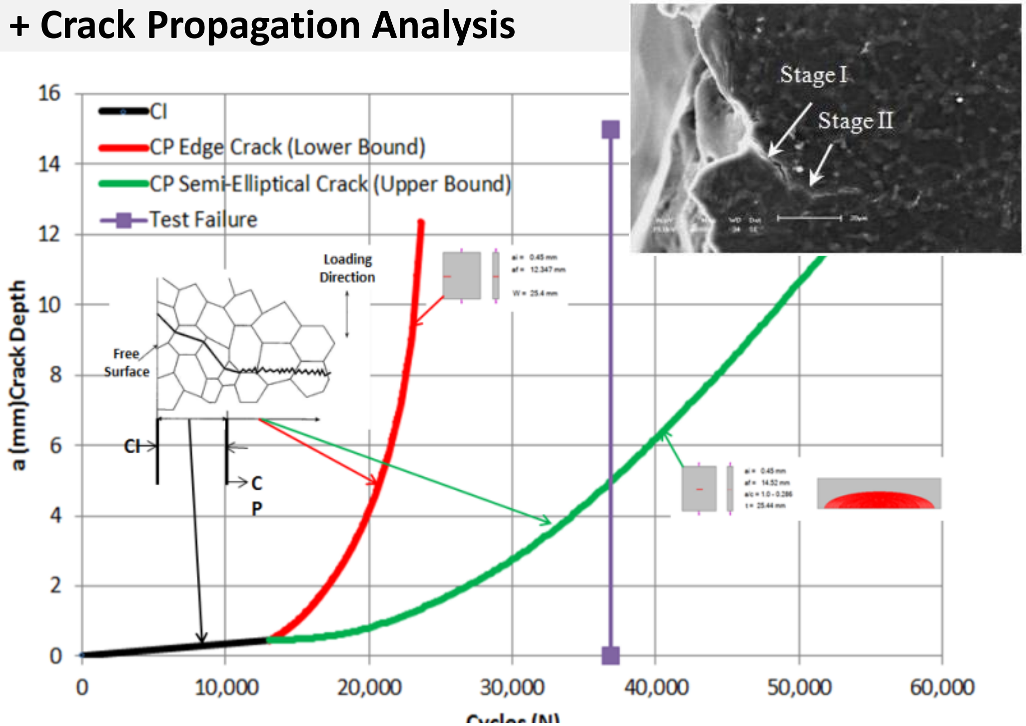
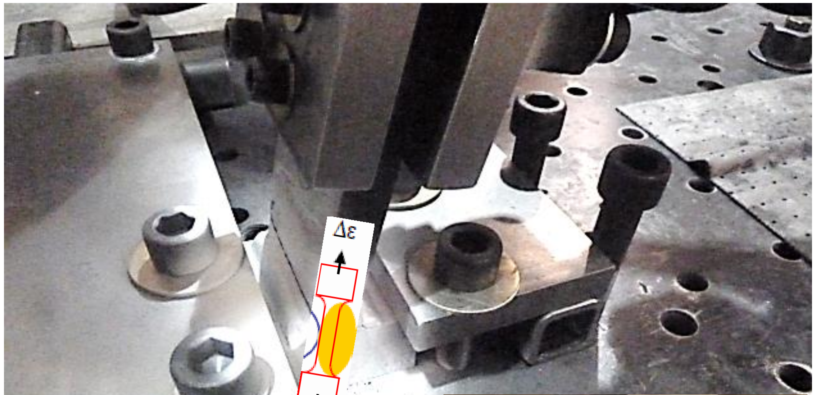
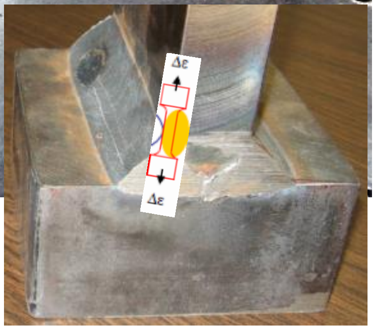
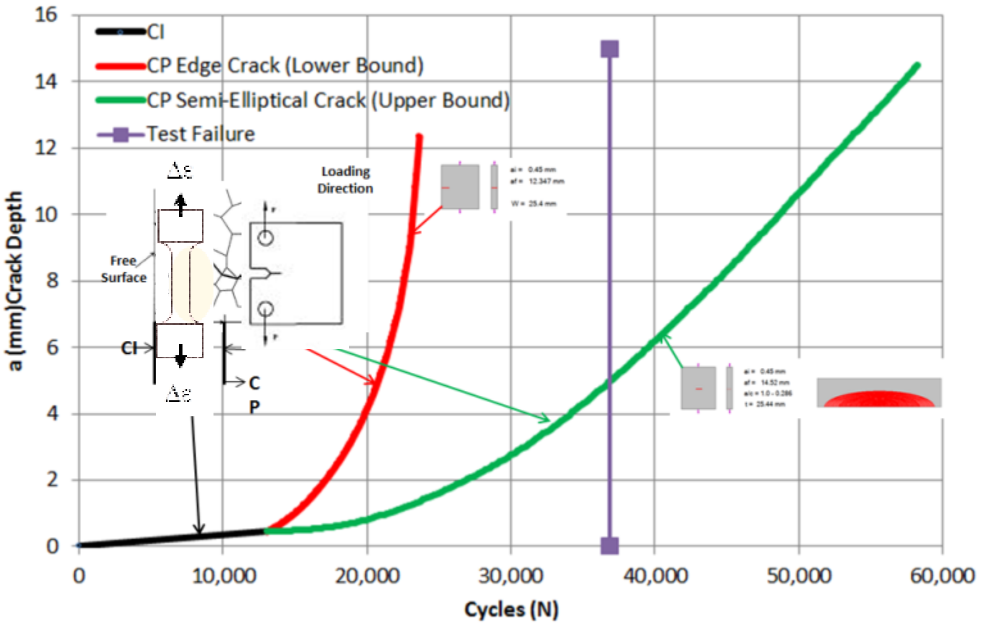
Total Fatigue Life – Combining the Crack Initiation + Crack Propagation Analysis





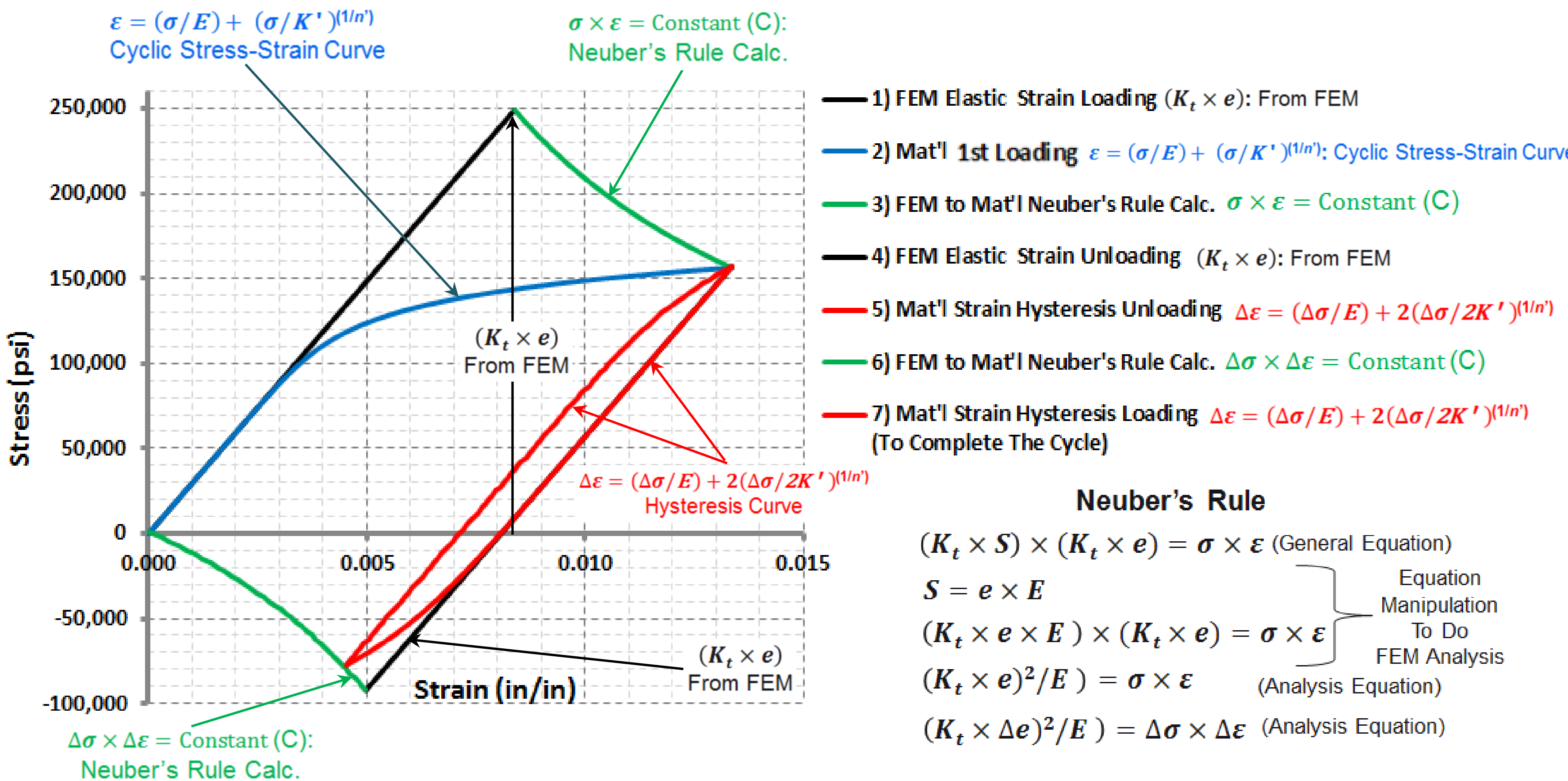






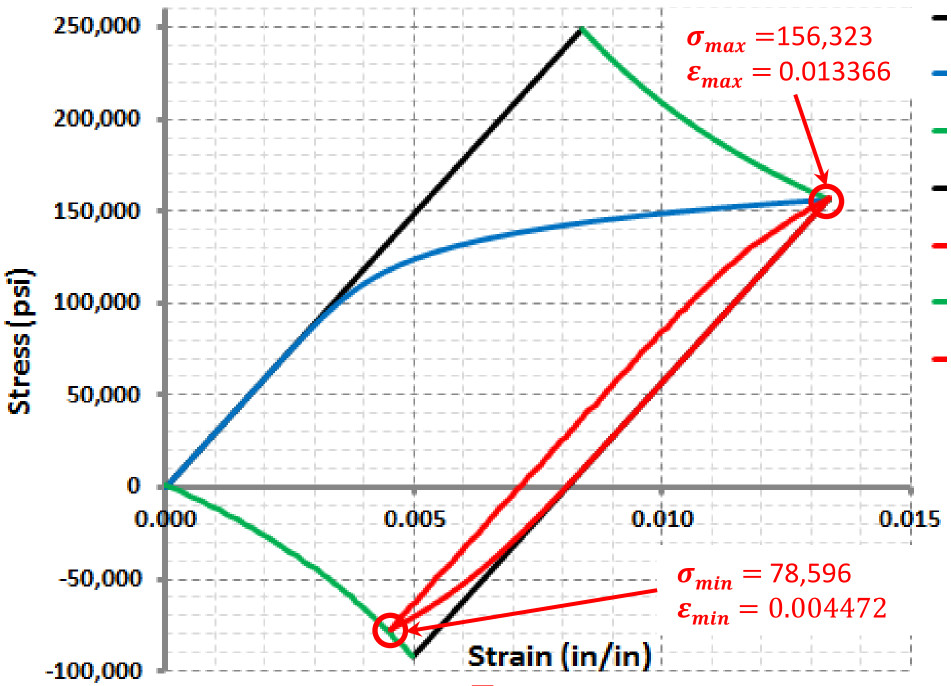
Crack Initiation Analysis Methodology/Process

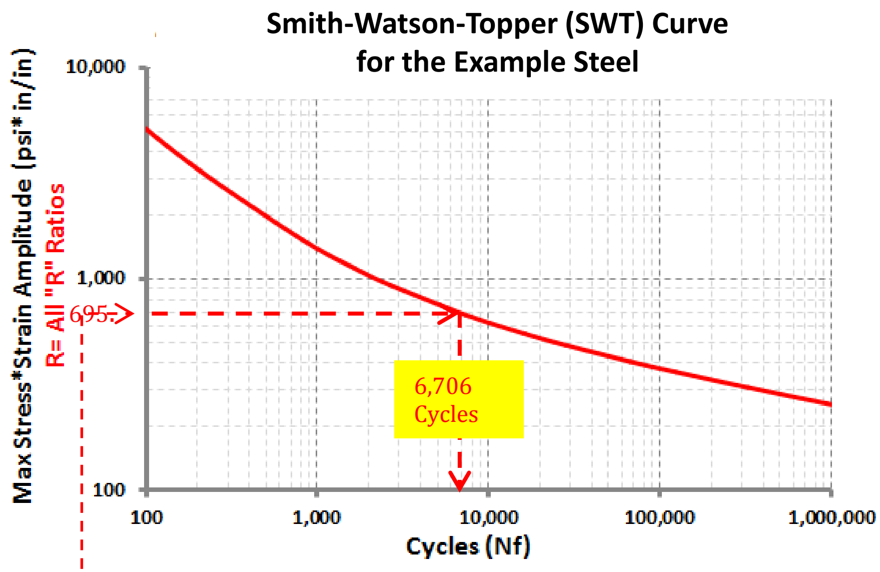
Convert the linear-elastic FEM stress-strain values to the actual steel nonlinear elastic-plastic stress-strain values. During that conversion, track those stresses and strains through the loading and then the unloading of the applied cycle to define the cycle that does the fatigue damage (see the closed 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.



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:





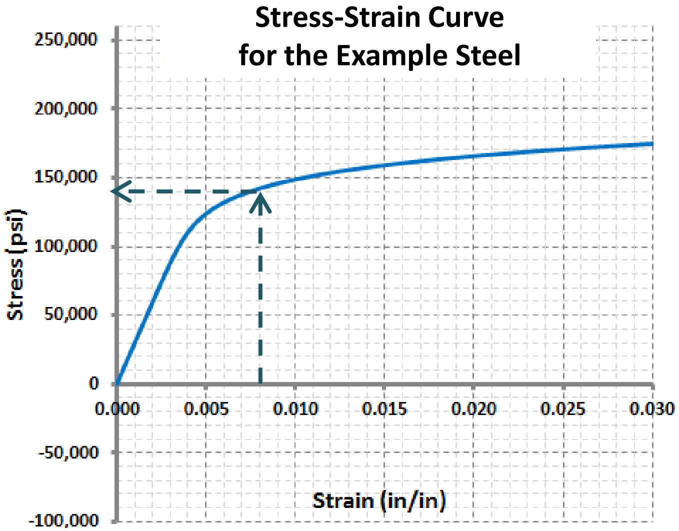
$\sigma_{max} = 156,323$
$\Delta\varepsilon/2 = (0.013366 - 0.004472)/2 = 0.004447$
$\sigma_{max} \times \Delta\varepsilon/2 = 695.$

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

Note: If there is a residual stress present it is input as an "initial offset" at the start of the stress-strain tracking of the cycle shown above.

Crack Initiation Analysis Methodology/Process

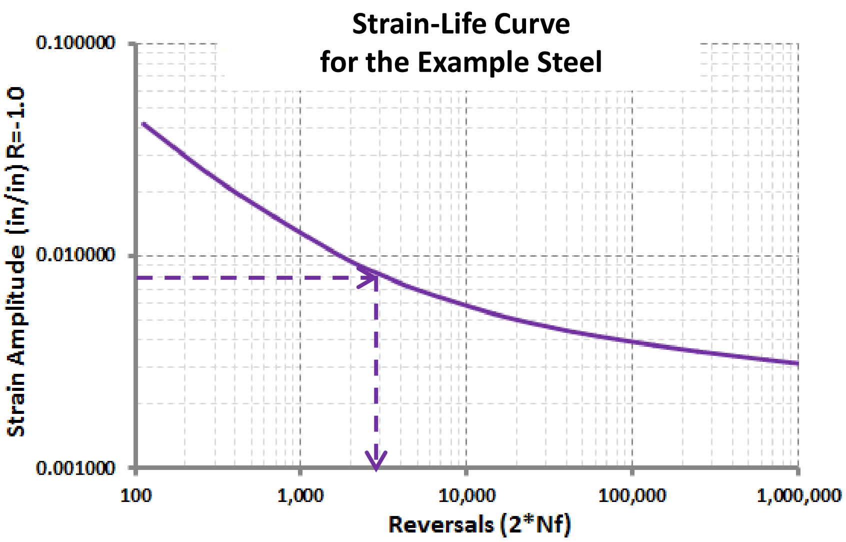
Develop the **"Iterative"** Smith-Watson-Topper (SWT) versus Fatigue Life (Nf) relationship/curve for the example steel. This is accomplished by "merging" the stress-strain curve with the strain life curve as shown below. **The SWT vs Nf relationship/curve is independent of R ratio and thus can be used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

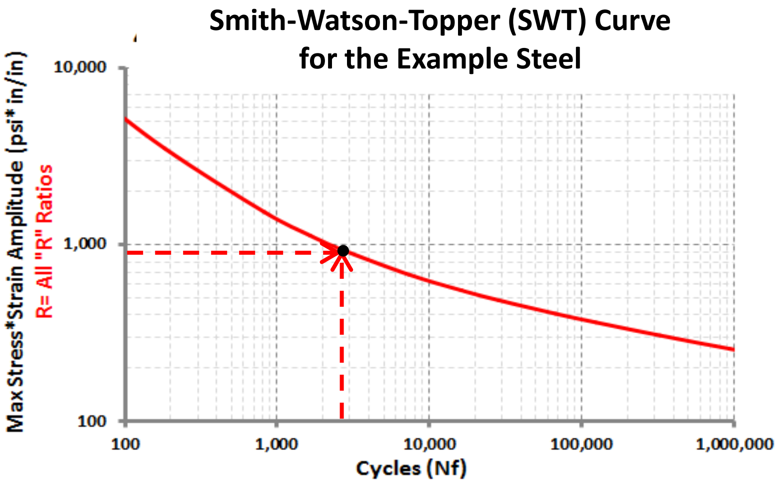


For a selected R=-1.0 strain value (ε) obtain it's maximum stress value (σmax) from the cyclic stress strain curve .

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 vs Nf curve.





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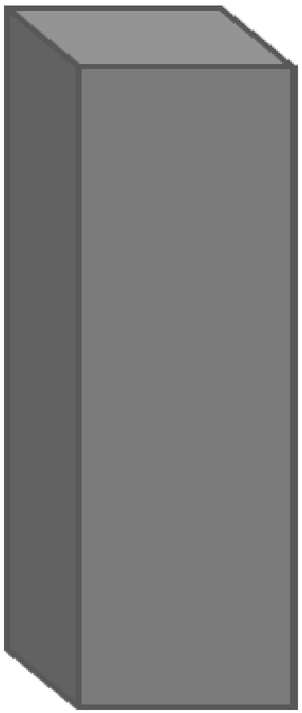
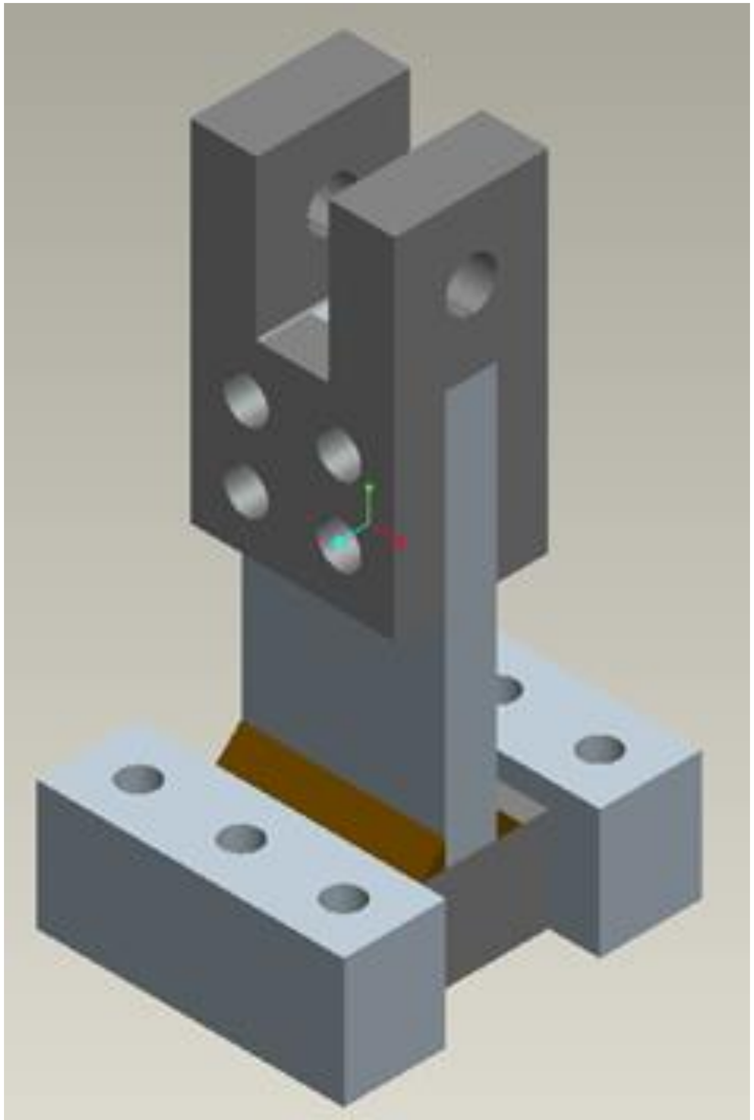
Total Fatigue Life: Crack Initiation and Crack Propagation Analysis

Load Carrying Weld

Specimen Configuration and Test Fixture/FEM Boundary Conditions





See Next Slide

Total Fatigue Life: Crack Initiation and Crack Propagation Analysis

Demonstrate Accurate Fatigue Life Predictions of the Less Complex Machined Sample Relative to <u>High Confidence</u> Component Test Data

+

Add the Complexities Introduced by Welding to that Machined Sample Fatigue Life Prediction Approach

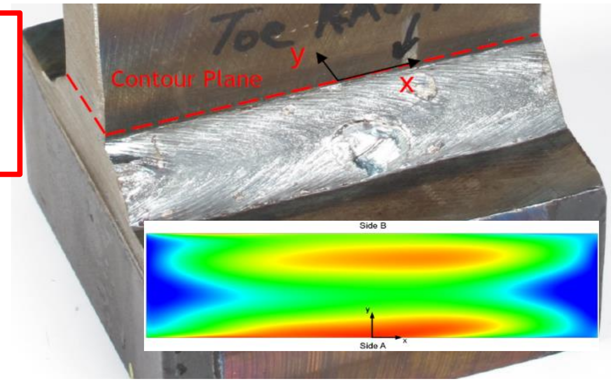
=

Produce Accurate Fatigue Life Predictions of the More Complex Welded Sample Relative to <u>High Confidence</u> Component Test Data?

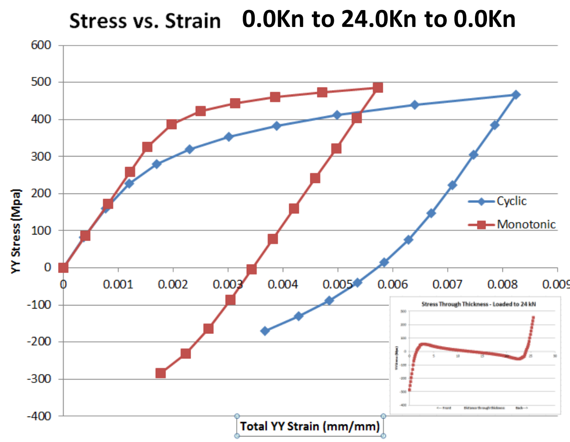
This presentation will focus on the "Machined Sample"

?

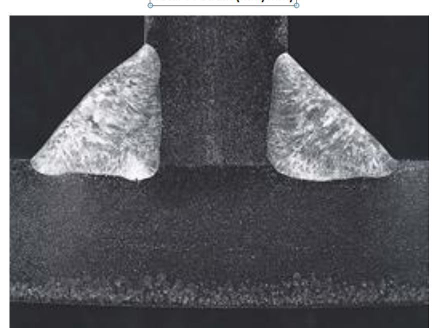
Residual stresses from welding

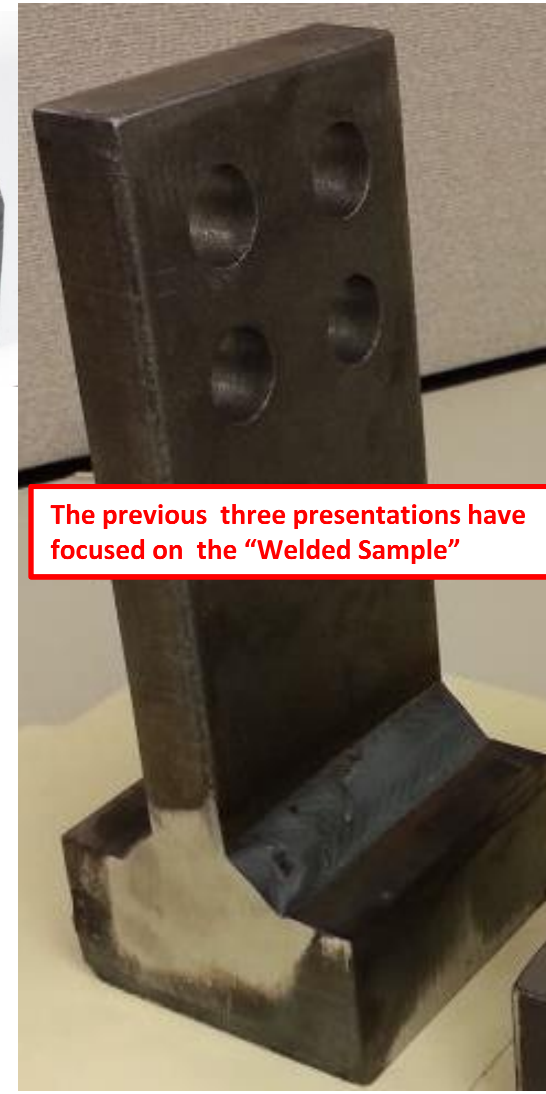


Residual Stresses from setup cycle applied <u>after residual stresses from welding</u>



Welded micro-structure influences





The previous three presentations have focused on the "Welded Sample"

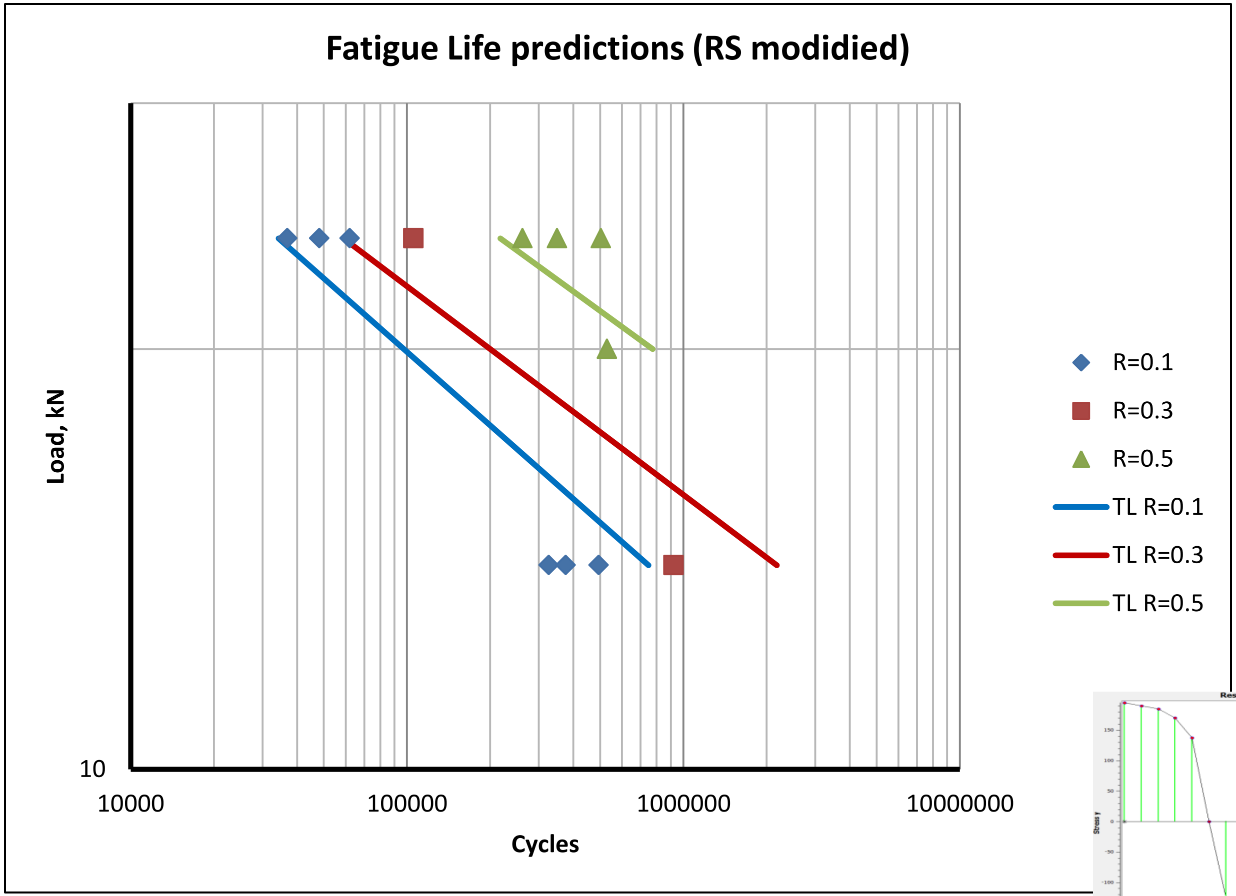
Welded Specimen Constant Amplitude Fatigue Test Results

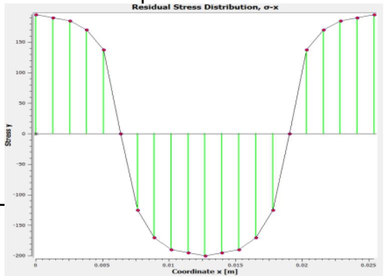
With time histories and videos of all tests

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 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

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Total Fatigue Life: Crack Initiation and Crack Propagation Analysis

Analytical/Experimental Results

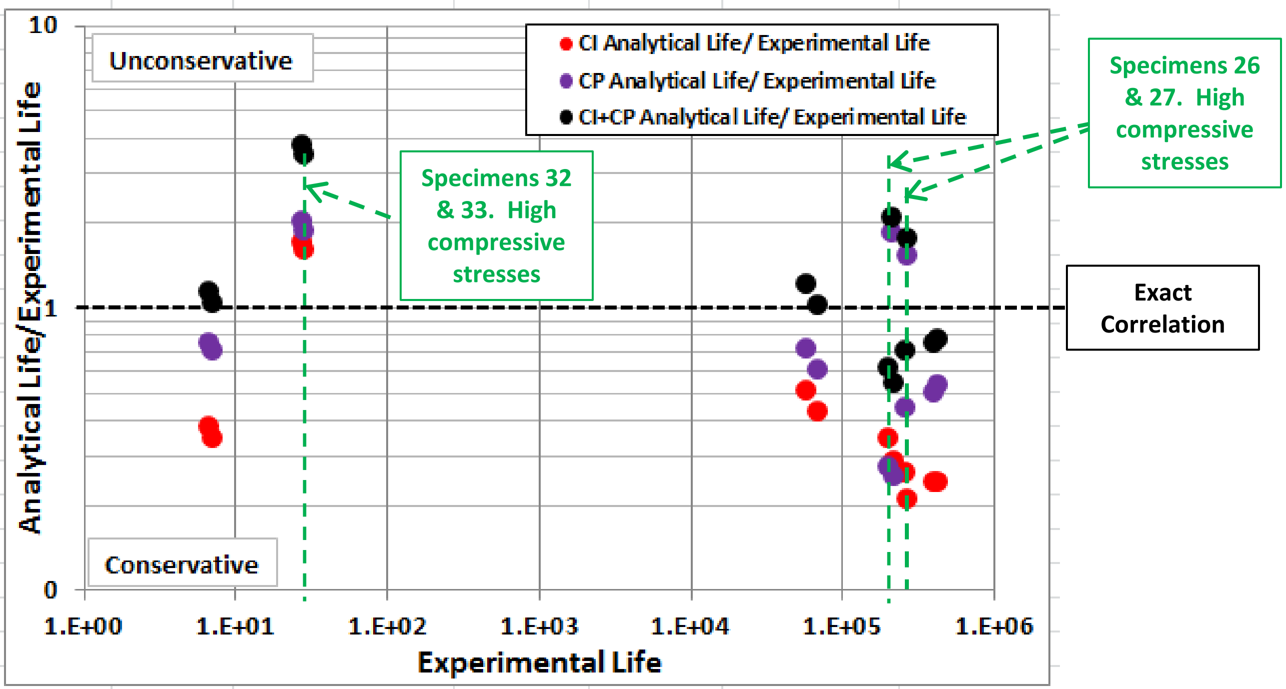
Specimen Number	Test Load Load Kn	Testing R Ratio Dimensionless	Max Stress Level Mpa	Max Strain Level ue	Setup Cycle R Ratio Dimensionless	Test Life (TL) Cycle Counter Cycles or Blocks	Test Life PV File Cycles or Blocks	Predicted CI Life Cycles or Blocks	Predicted CP Life Cycles or Blocks	Predicted CI+CP Life Cycles or Blocks	Fatigue Exp. #2 Predicted CI Life Cycles or Blocks	CI+CP Life/ Test Life (TL) Dimensionless
22	24	0.3	870.44	4150	0.0	266,012	266,001	68,750	117,374	186,124	58,033	0.70
25	24	0.3	870.44	4150	0.3	218,671	218,658	62,430	54,606	117,036	57,765	0.54
35	24	0.3	870.44	4150	0.3	200,464	200,446	68,180	54,753	122,786	57,876	0.61
19	24	0.1	870.44	4150	0.1	58,481	58,470	29,360	41,354	70,714	25,743	1.21
23	24	0.1	870.44	4150	0.1	70,011	70,000	29,710	41,920	71,630	25,944	1.02
20	18	0.1	652.83	3113	0.1	411,745	411,735	98,750	205,590	304,340	83,575	0.74
24	18	0.1	652.83	3113	0.0	424,431	424,205	101,900	225,421	327,321	85,701	0.77
26	10.8	-1.0	391.70	1868	None	214,765	214,656	57,030	391,856	448,886	52,666	2.09
27	10.8	-1.0	391.70	1868	None	271,951	271,836	56,870	415,417	472,287	52,613	1.74
29	24	*Block: 0.1/.5	870.44	4150	0.1	7.2	7.3	2.5	5.0	7.5	2.2	1.04
30	24	*Block: 0.1/.5	870.44	4150	0.1	6.7	6.7	2.5	5.0	7.6	2.3	1.13
32	24	Variable Amplitude	870.44	4150	None	28.0	28.4	47.5	56.4	104.0	43.0	3.71
33	24	Variable Amplitude	870.44	4150	None	29.0	29.0	46.1	53.7	99.9	35.6	3.44

Note: *5,000 24Kn R=0.1 Cycles followed by 40,000 24Kn R=0.5 Cycles

Observations:

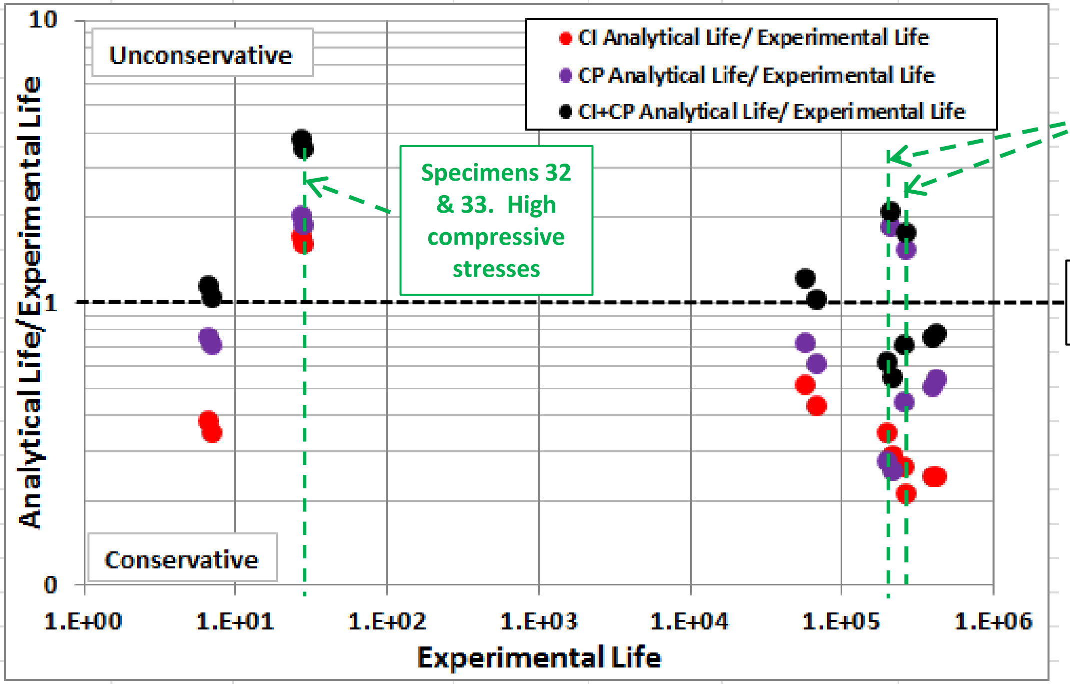
1) For the CI + CP fatigue life predictions, only peak valley histories with a lot of high compressive stress cycles vary significantly from a "correlation factor" of "1".

2) Both the CI and CP fatigue life predictions significantly "over predict" the fatigue life for the variable amplitude PV history.



Total Fatigue Life: Crack Initiation and Crack Propagation Analysis

Analytical/Experimental Results

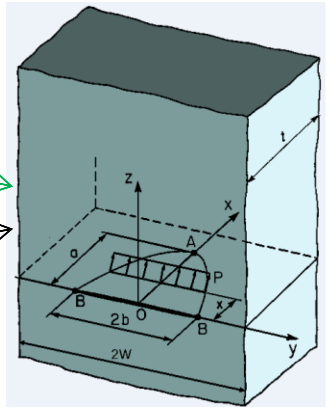


Explanation of Possible Need for Empirical Compressive Stress Correction

A geometry and loading that grows cracks simultaneously from the front face and back face (meeting at mid-thickness) may not "fit well with" the boundary conditions of the Weight Function Stress Intensity Solution "the way it is used" in this CP analysis. The "valley" compressive bending stress (S=Mc/I) continuously increases on the front face crack (being analyzed) because the "c", "I", and "neutral axis" are continuously changing as the crack advances on the back face.

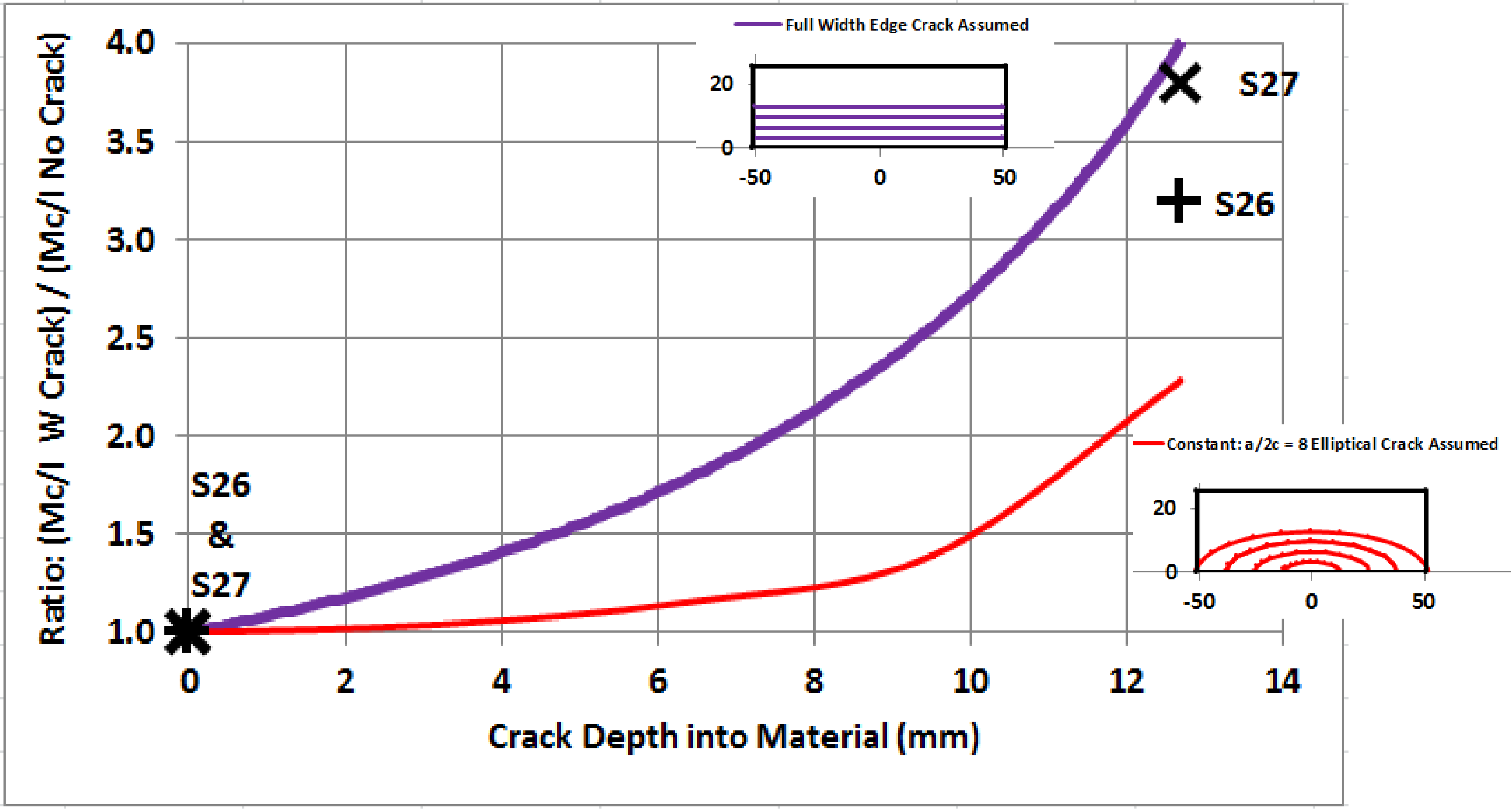
Specimens 26, 27, 32, and 33 "don't fit well" to SIF as used

Specimens 19, 20, 22, 23, 24, 25, 29, 30, and 35 "do fit well" to SIF as used



Total Fatigue Life: Crack Initiation and Crack Propagation Analysis

For a Crack of increasing Size: Calculated (Mc/I With Crack) / (Mc/I No Crack) Compared to Empirical Compressive Stress Correction From the Start and End of the Fatigue Predictions Made Using the Method Described on the Previous Slide



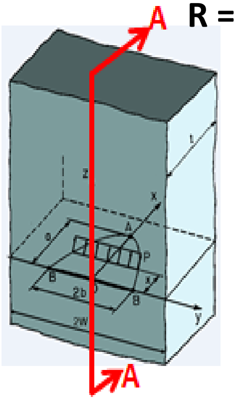
Further Description of Analysis Method: Only the compressive stress cycles in the peak-valley history where increased by this "linear empirical compressive stress correction trend". It calculated 1.00 times the stress at the start of the cycling and increased the stress at each subsequent compressive valley cycle by .1/10,000 (tension and/or compression) cycles until failure. At the beginning of the test both factors were equal to 1.0 (points on the left side of the plot). At failure the factors were calculated by dividing the maximum compressive stress at failure by the initial maximum compressive stress (points on the side side of the plot). Specimen 26 Ratio =3.16, Specimen 27 Ratio =3.80.

Total Fatigue Life: Crack Initiation and Crack Propagation Analysis

Empirical Compressive Stress Correction

Caution: The technique shown below should be implemented within the software code as a function of a and c (b). Because that was not feasible it was simulated externally as a function of cycles (N)

R = Positive



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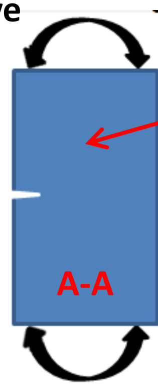
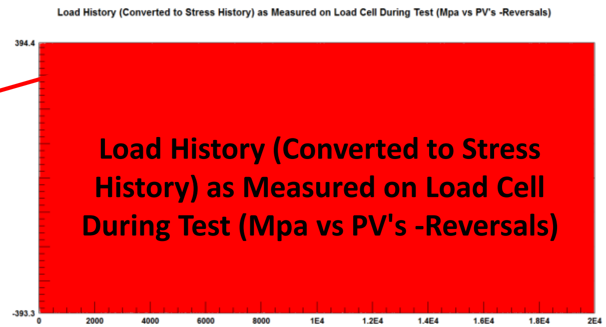
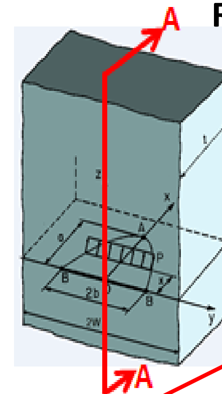




R = Negative



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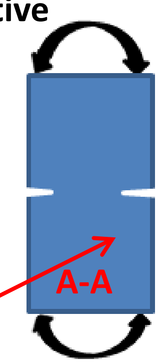
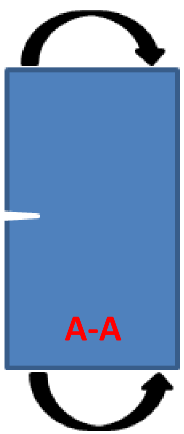
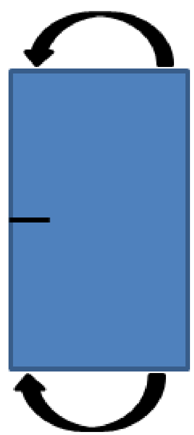
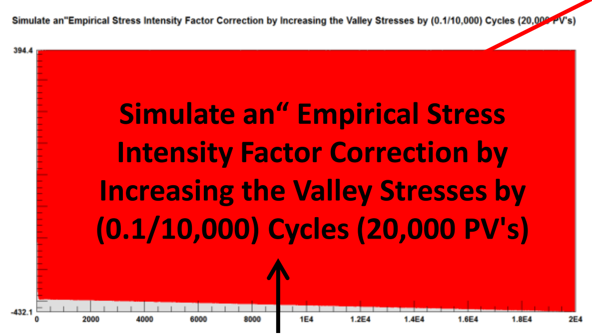
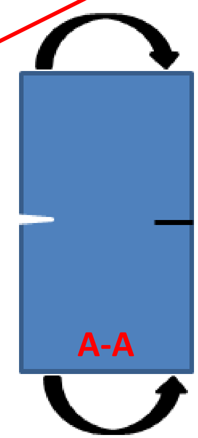


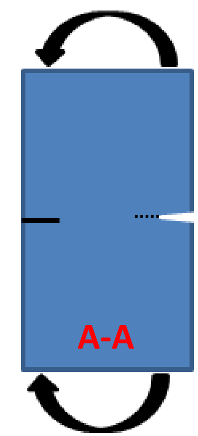
"Engineering is the art of being approximately right instead of exactly wrong"











+S=M(c/l) Consistent with CG Stress Intensity Solution

-S=M(c/l) Consistent with CG Stress Intensity Solution

Used this history to predict the 10.8Kn R=-1.0 tests and got correlation factors of 0.90 & 0.82. Applied same scaling factor to 24Kn Variable Amplitude tests & got correlation factors of 1.08 &1.00

-S=M(c/l) Consistent with CG Stress Intensity Solution

-S=M(c/l) Not consistent with CG Stress Intensity Solution (c/l is constantly increasing)

Total Fatigue Life: Crack Initiation and Crack Propagation Analysis

Analytical/Experimental Results (With Empirical Compressive Stress Correction)

Specimen Number	Test Load Kn	Test R Ratio Dimensionless	Max Stress Level Mpa	Max Strain Level ue	Setup Cycle R Ratio Dimensionless	Test Life (TL) Cycle Counter Cycles or Blocks	Test Life PV File Cycles or Blocks	Predicted CI Life Cycles or Blocks	Predicted CP Life Cycles or Blocks	Predicted CI+CP Life Cycles or Blocks	Fatigue Exp. #2 Predicted CI Life Cycles or Blocks	CI+CP Life/ Test Life (TL) Dimensionless
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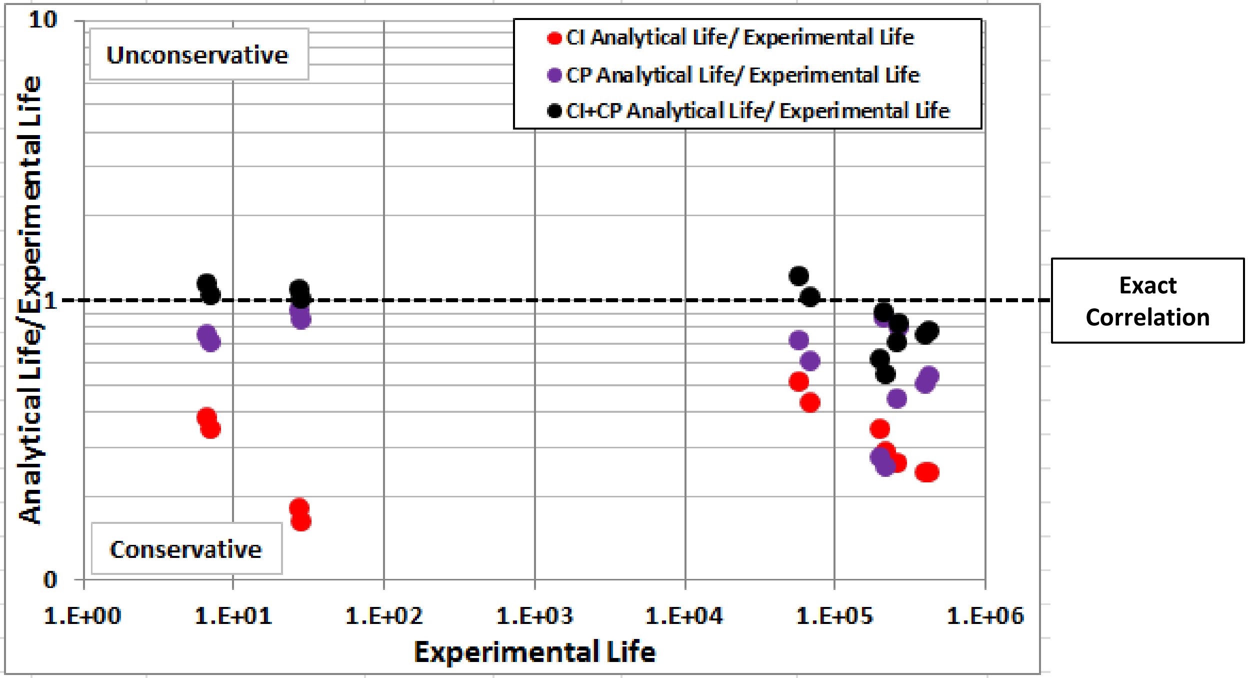
24	18	0.1	652.83	3113	0.0	424,431	424,205	101,900	225,421	327,321	85,701	0.77
26	10.8	-1.0	391.70	1868	None	214,765	214,656	9,382	184,446	193,828	8,765	0.90
27	10.8	-1.0	391.70	1868	None	271,951	271,836	6,489	215,559	222,048	6,107	0.82
29	24	*Block: 0.1/.5	870.44	4150	0.1	7.2	7.3	2.5	5.0	7.5	2.2	1.04
30	24	*Block: 0.1/.5	870.44	4150	0.1	6.7	6.7	2.5	5.0	7.6	2.3	1.13
32	24	Variable Amplitude	870.44	4150	None	28.0	28.4	5.0	25.3	30.3	3.0	1.08
33	24	Variable Amplitude	870.44	4150	None	29.0	29.0	4.7	24.3	29.0	2.8	1.00

Note: *5,000 24Kn R=0.1 Cycles followed by 40,000 24Kn R=0.5 Cycles



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Total Fatigue Life: Crack Initiation and Crack Propagation Analysis

Examine, in More Detail, the Analytical/Experimental Results of a Typical Test – Specimen 30

Specimen Number	Test Load Kn	Test R Ratio Dimensionless	Max Stress Level Mpa	Max Strain Level ue	Setup Cycle R Ratio Dimensionless	Test Life (TL) Cycle Counter Cycles or Blocks	Test Life PV File Cycles or Blocks	Predicted CI Life Cycles or Blocks	Predicted CP Life Cycles or Blocks	Predicted CI+CP Life Cycles or Blocks	Fatigue Exp. #2 Predicted CI Life Cycles or Blocks	CI+CP Life/ Test Life (TL) Dimensionless
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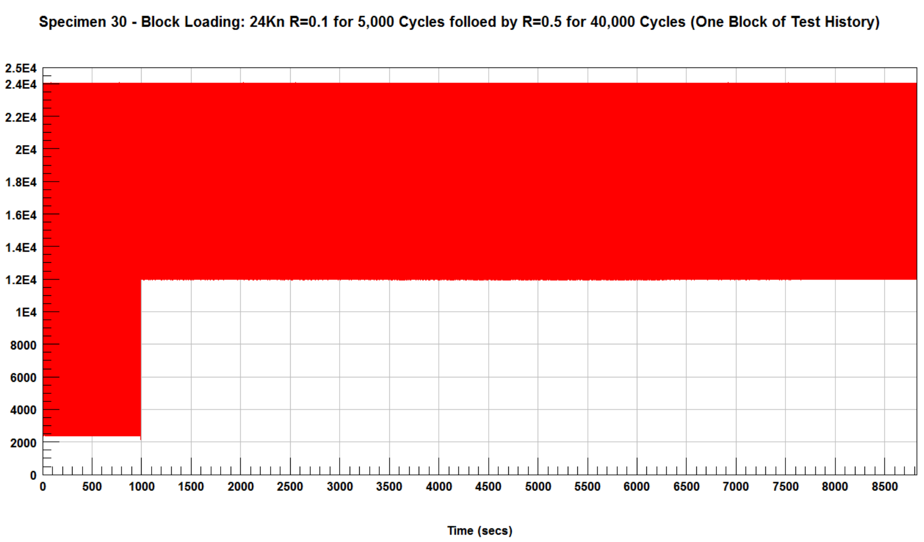
33	24	Variable Amplitude	870.44	4150	None	29.0	29.0	4.7	24.3	29.0	2.8	1.00

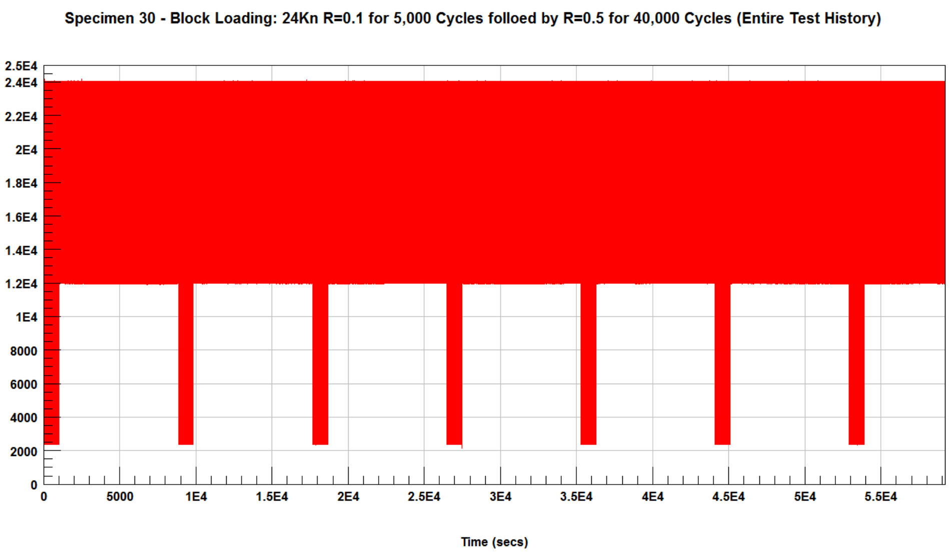
Note: *5,000 24Kn R=0.1 Cycles followed by 40,000 24Kn R=0.5 Cycles

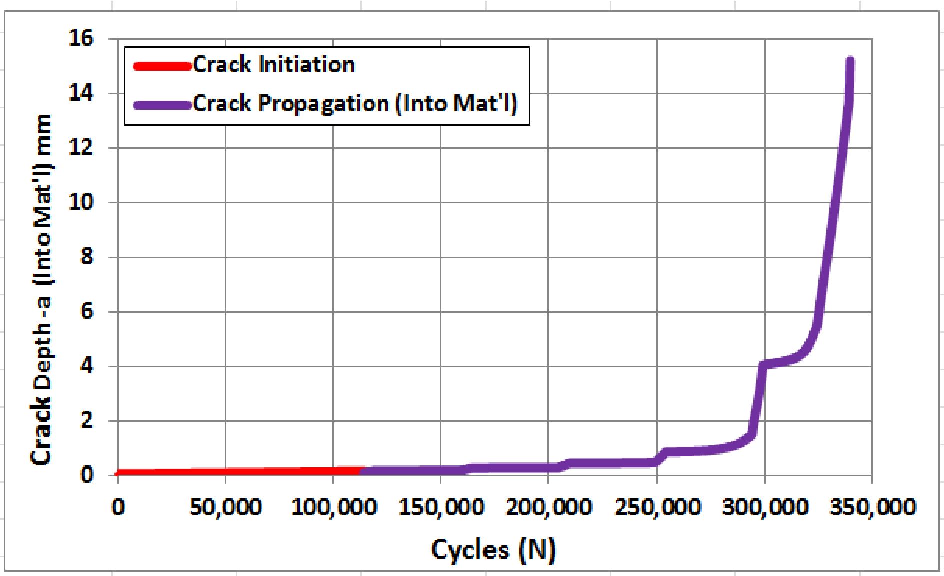
Note that this was one of the nine (out of thirteen) samples that needed no empirical compressive stress correction.

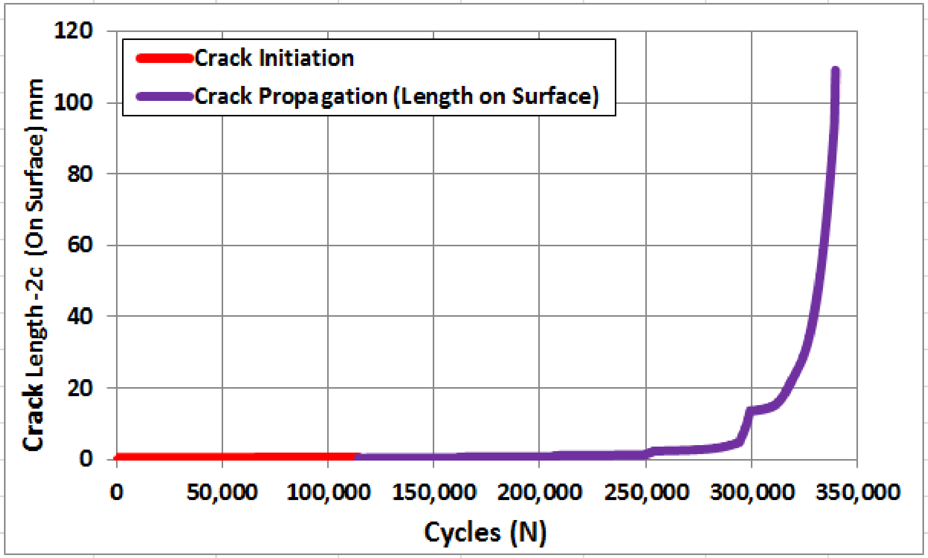
Total Fatigue Life: Crack Initiation and Crack Propagation Analysis

Analytical/Experimental Results (With Empirical Compressive Stress Correction)



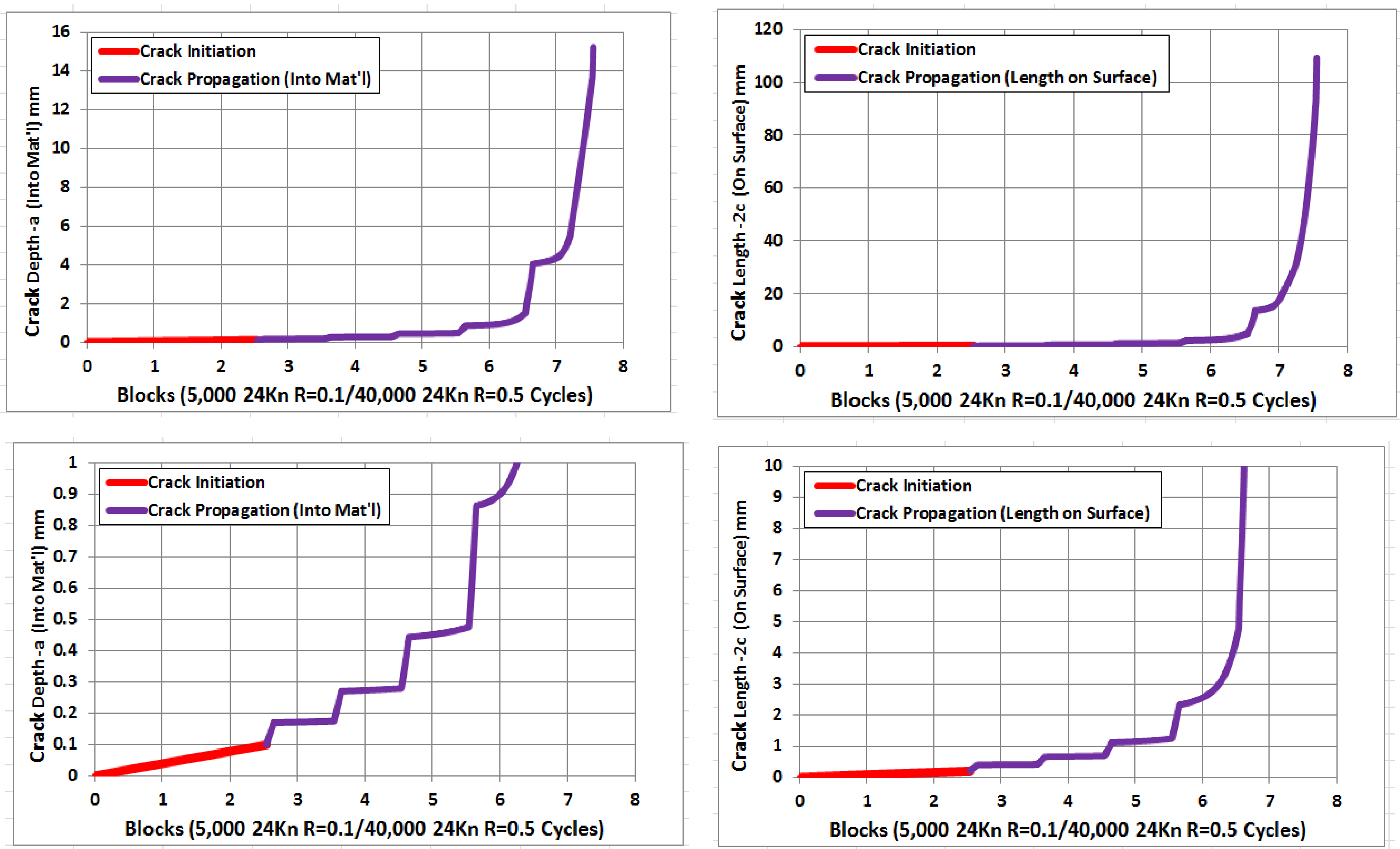




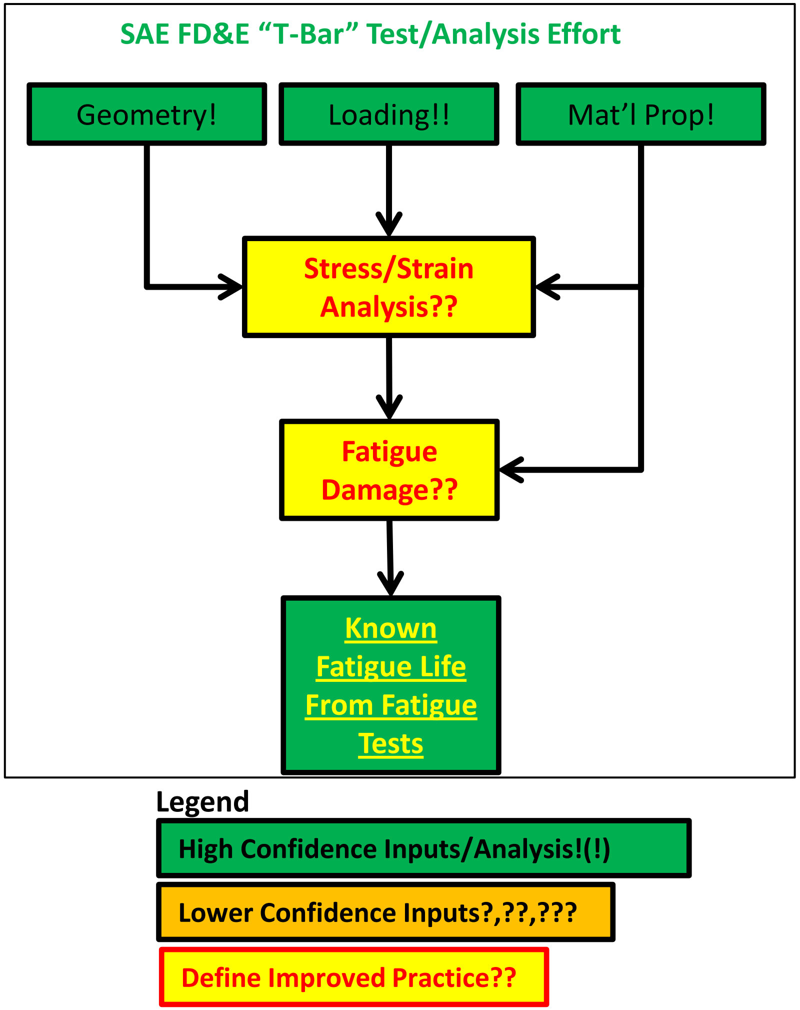


Total Fatigue Life: Crack Initiation and Crack Propagation Analysis

Analytical/Experimental Results (With Empirical Compressive Stress Correction)



Total Fatigue Life: Crack Initiation and Crack Propagation



It would be very difficult to consistently stop a "crack initiation evaluation test" at a consistent crack size (and shape) when evaluating a "Life Prediction Improved Practice" because of the very shallow slope of the a vs N curve in that region. Attempting to do that would probably be interpreted as much more significant fatigue life scatter in the test results.

Total Fatigue Life: Crack Initiation and Crack Propagation

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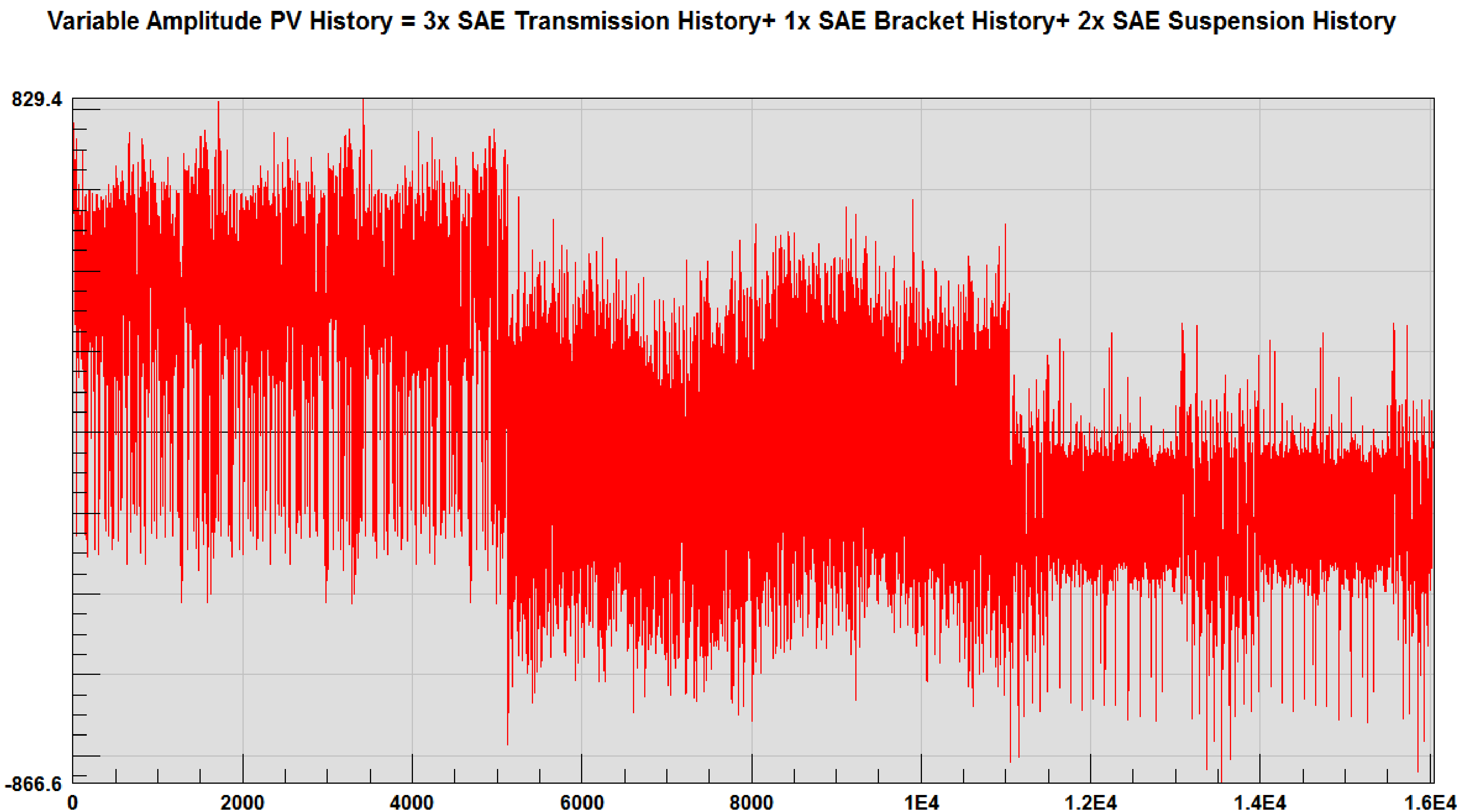
20	18	0.1	652.83	3113	0.1	411,745	411,735	98,750	205,590	304,340	83,575	0.74
24	18	0.1	652.83	3113	0.0	424,431	424,205	101,900	225,421	327,321	85,701	0.77
26	10.8	-1.0	391.70	1868	None	214,765	214,656	57,030	391,856	448,886	52,666	2.09
27	10.8	-1.0	391.70	1868	None	271,951	271,836	56,870	415,417	472,287	52,613	1.74
29	24	*Block: 0.1/.5	870.44	4150	0.1	7.2	7.3	2.5	5.0	7.5	2.2	1.04
30	24	*Block: 0.1/.5	870.44	4150	0.1	6.7	6.7	2.5	5.0	7.6	2.3	1.13
32	24	Variable Amplitude	870.44	4150	None	28.0	28.4	47.5	56.4	104.0	43.0	3.71
33	24	Variable Amplitude	870.44	4150	None	29.0	29.0	46.1	53.7	99.9	35.6	3.44

Note: *5,000 24Kn R=0.1 Cycles followed by 40,000 24Kn R=0.5 Cycles

Both CI and CP Life Predictions Significantly Exceed the Test Lives. Possible explanation for CP addressed earlier (Simultaneous "Back-face" Crack. <u>But what is reason for CI over-prediction?</u>

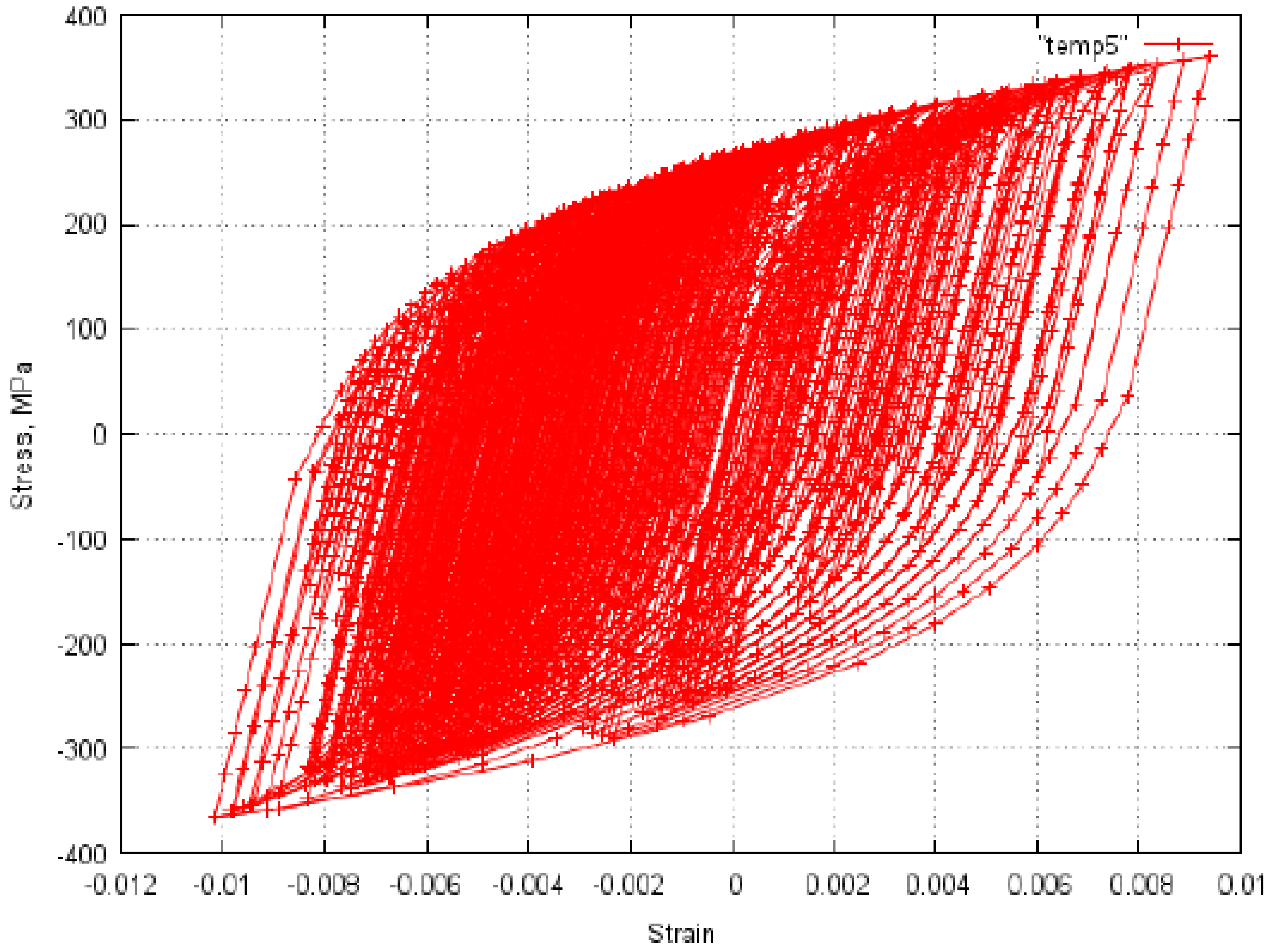
Total Fatigue Life: Crack Initiation and Crack Propagation Analysis

Analytical/ExperimentalResults



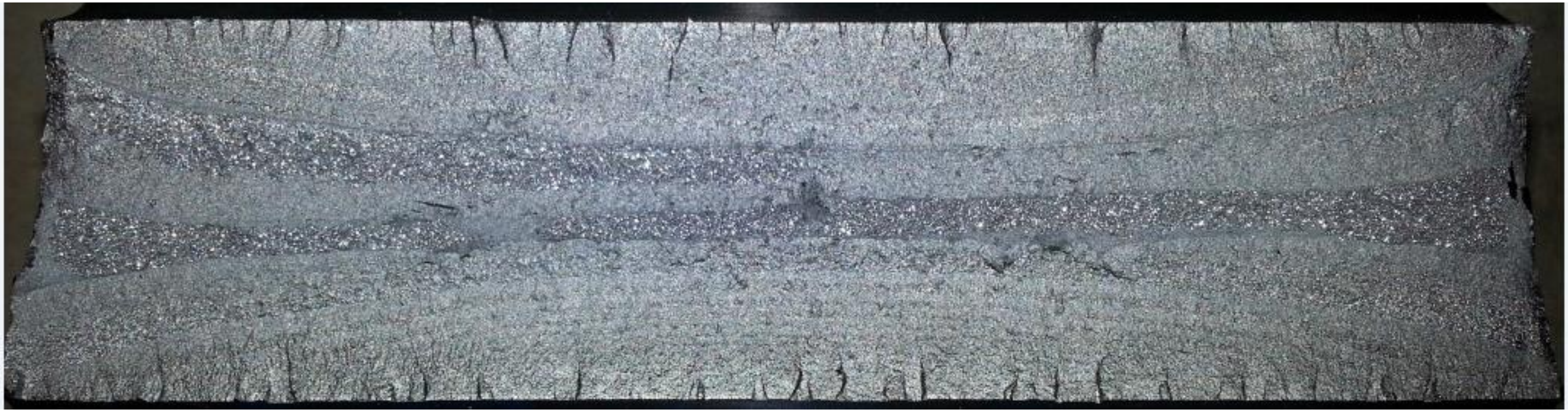
Analytical/Experimental Results

Local Stress and Strain Response:



Total Fatigue Life: Crack Initiation and Crack Propagation Analysis

<u>**Work Currently in Progress to Sort out Difference between Analytical and Experimental Results**</u>



Specimen 32 - Lamda Technologies is "Reading" Fracture surface

Specimen 33 - Nima Shamsaei (at Mississippi State) is "Reading" Fracture surface

Total Fatigue Life: Crack Initiation and Crack Propagation Analysis

Analytical/Experimental

Determine by "measuring the CP striations" from the two fracture surfaces (on the preceding slide) back from failure as far as possible to quantify how much of the life was spent advancing an identifiable crack from its "initiation".

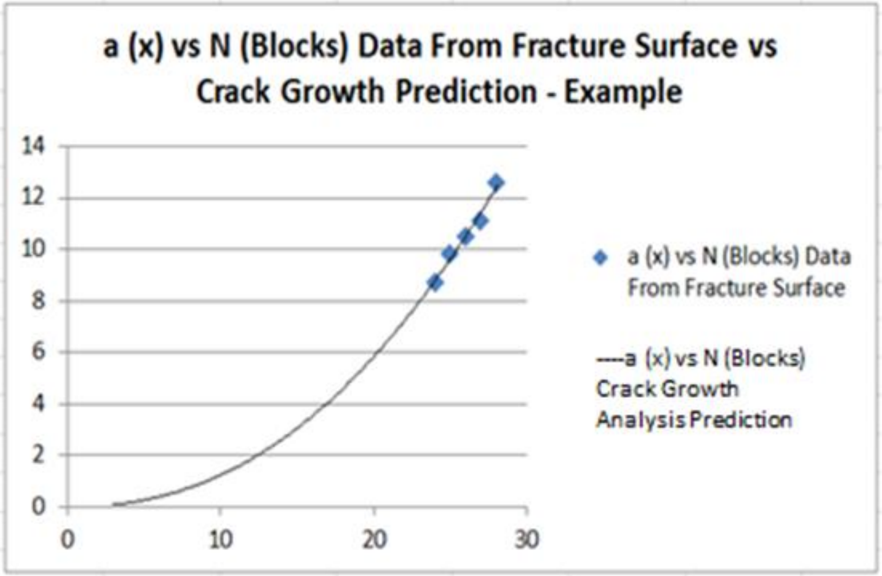
Please Provide the Table as Shown Below

The SAE FD&E Committee Will Provide the Crack Growth Prediction and the Correlation as Shown Below

Example of Measurements Needed **(+/- 2mm acceptable)**
Numbers in table are not real - just show data trend

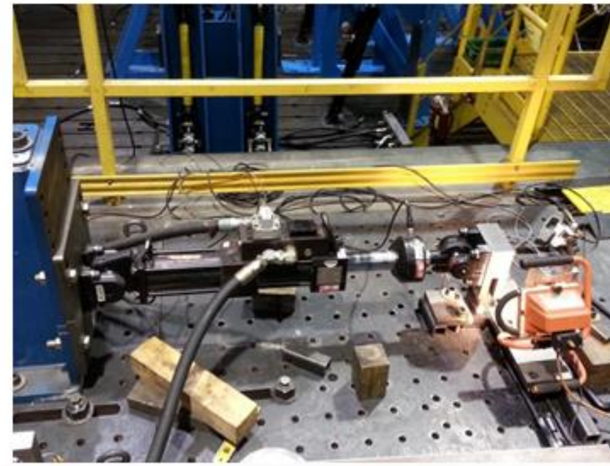
		Plane B		Plane C	
Measurement	Test Block	x (mm)	z (mm)	x (mm)	z (mm)
1	Failure	12.6	0	12.6	50.4
2	28	11.1	0	6.6	50.4
3	27	10.5	0	0	50.4
4	26	9.8	0	0	45.5
5	25	8.7	0	0	43.2
6	24	8.5	0	0	41.7
...	...	...	...	...	...
.....	.....	.....	.....	.....	.....

Read the surface as far back to the origin as you can go
When difficult - best estimate of measurements OK

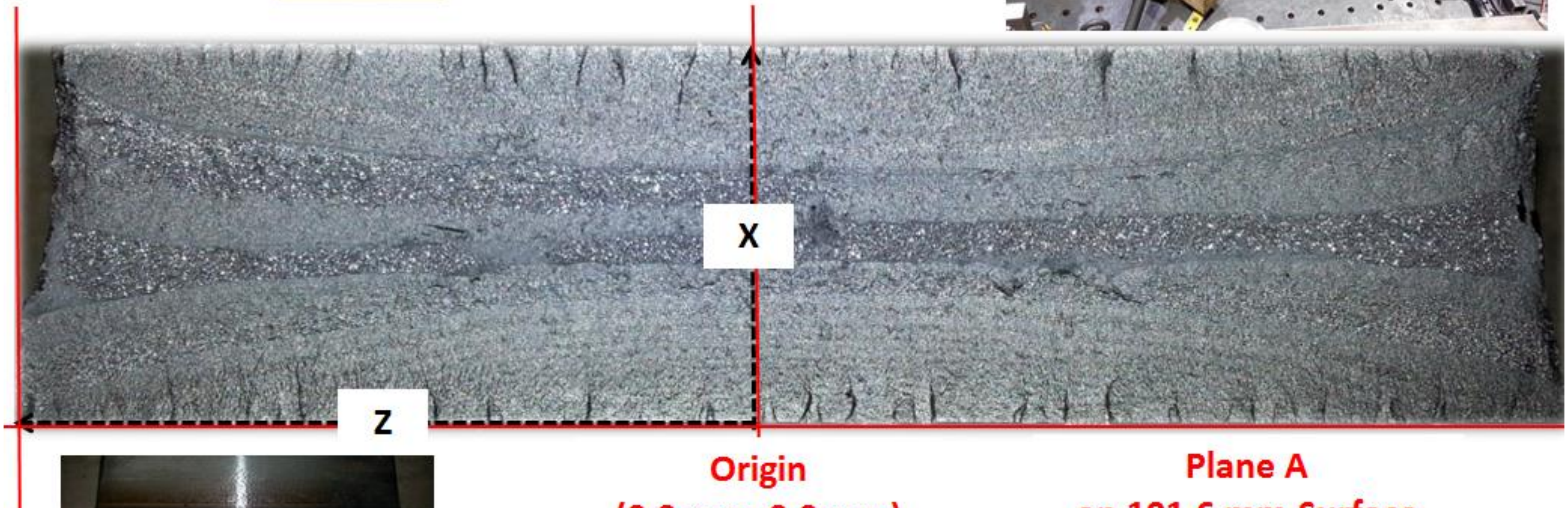


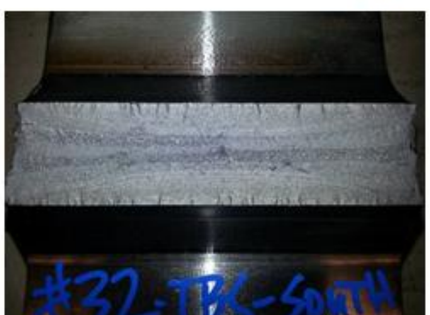
Total Fatigue Life: Crack Initiation and Crack Propagation Analysis

Plane B
At Center of Width or Center of Semielliptical Fracture Surface
(Depends on Fracture Surface Origin Side to Side Location)



Plane c
on 25.4 mm Surface

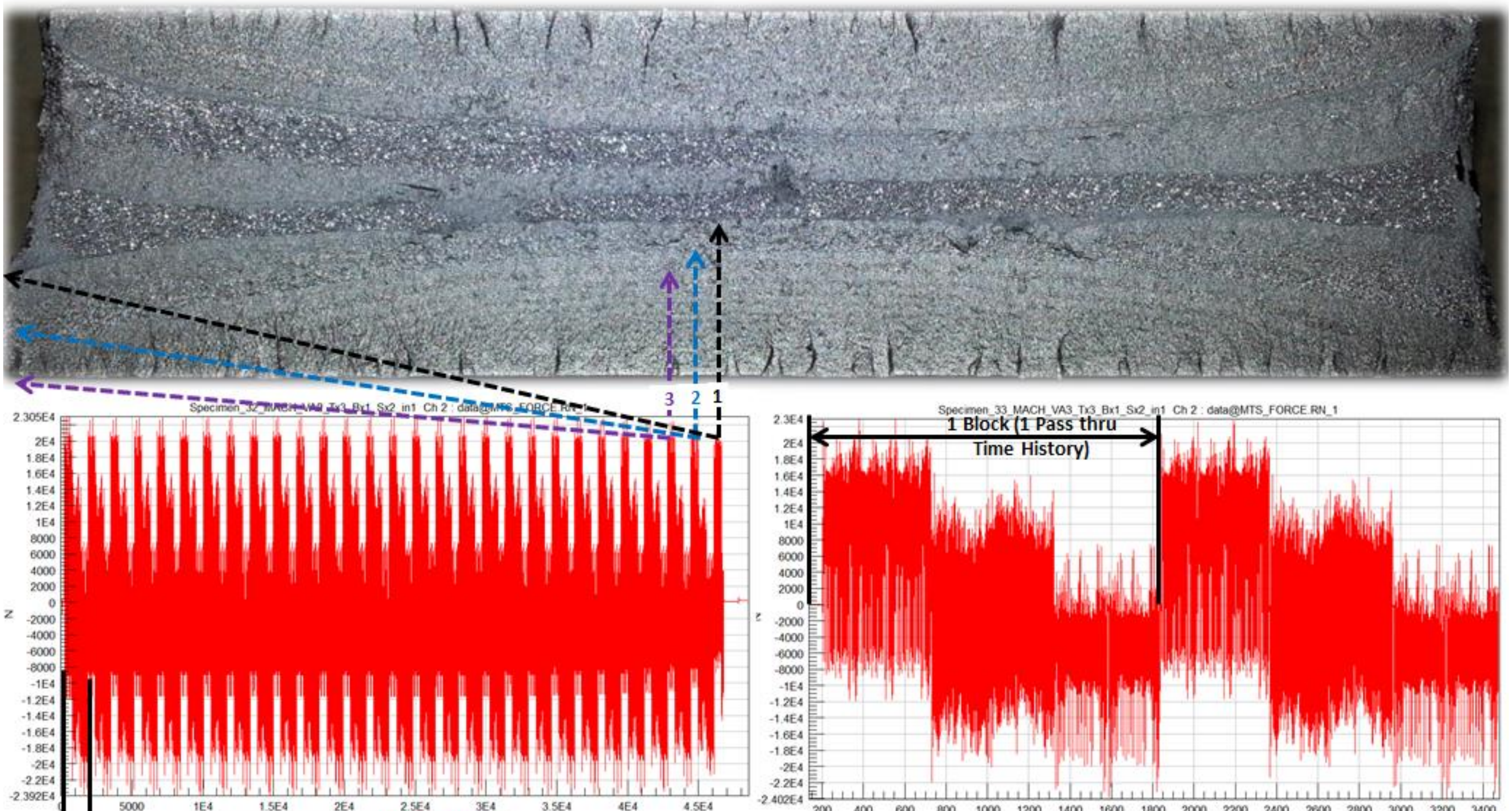




Origin
(0.0 mm, 0.0 mm)
(X,Z)

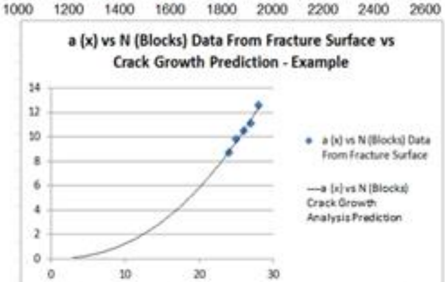
Plane A
on 101.6 mm Surface

Total Fatigue Life: Crack Initiation and Crack Propagation Analysis



1 Block (1 Pass thru Time History)

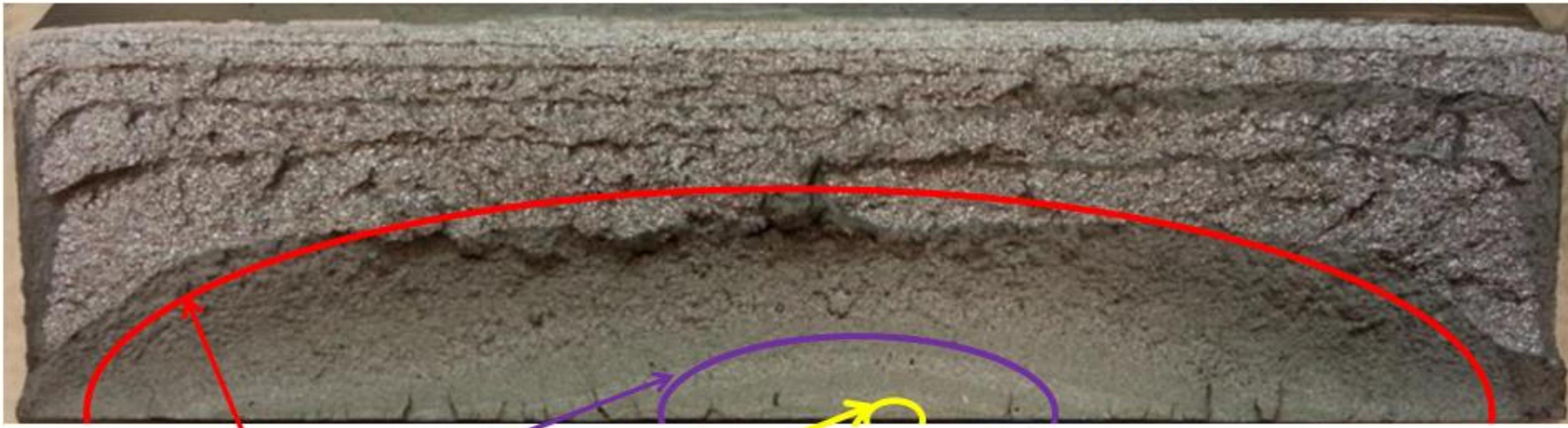
Example of Measurements Needed (+/- 2mm acceptable) Numbers in table are not real - just show data trend					
		Plane B		Plane C	
Measurement	Test Block	x (mm)	z (mm)	x (mm)	z (mm)
1	Failure	12.6	0	12.6	50.4
2	28	11.1	0	6.6	50.4
3	27	10.5	0	0	50.4
4	26	9.8	0	0	45.5
5	25	8.7	0	0	43.2
6	24	8.5	0	0	41.7
...	...	...	...	...	...
.....	.....	.....	.....	.....	.....
Read the surface as far back to the origin as you can go When difficult - best estimate of measurements OK					



Total Fatigue Life: Crack Initiation and Crack Propagation Analysis

Analytical Crack Growth Prediction Results vs Experimental Results

Photos below are approximately 1.64 x part actual dimensions



At Failure (100% Life)
a = 13.75mm
2c = 94.47mm

At 95% Life
a = 5.16mm
2c = 26.47mm

At 83% Life
a = 1.00mm
2c = 3.01mm

This indicates that 82% of the fatigue life is consumed initiating and growing to a detectable / observable size.