Predicting Total Fatigue Life (Crack Initiation and Crack Propagation)

Presented to the SAE FD&E Committee
at Cincinnati, OH on 15 April 2013
(Prepared by Tom Cordes)

→ 1. **Overview of Effort**

2. **Machined Samples Analysis/Test Results Comparison Summary**

3. **24Kn R=0.1(5,000 cycles)/0.5(40,000 cycles) Block Loading Machined Sample Detailed Analysis/Test Comparison**

4. **24Kn Variable Amplitude Machined Sample Block Loading Analysis/Test Comparison – Issues?**

5. **Crack Initiation and Crack Propagation Analysis Methodology Background (If time allows)**

"ENGINEERING IS THE ART OF MODELING MATERIALS WE DO NOT WHOLLY UNDERSTAND, INTO SHAPES WE CANNOT PRECISELY ANALYZE, SO AS TO WITHSTAND FORCES WE CANNOT PROPERLY ASSESS, IN SUCH A WAY THAT THE PUBLIC HAS NO REASON TO SUSPECT THE EXTENT OF OUR IGNORANCE."

DR. A.R. DYKES, CHAIRMAN, BRITISH INSTITUTE OF STRUCTURAL ENGINEERS

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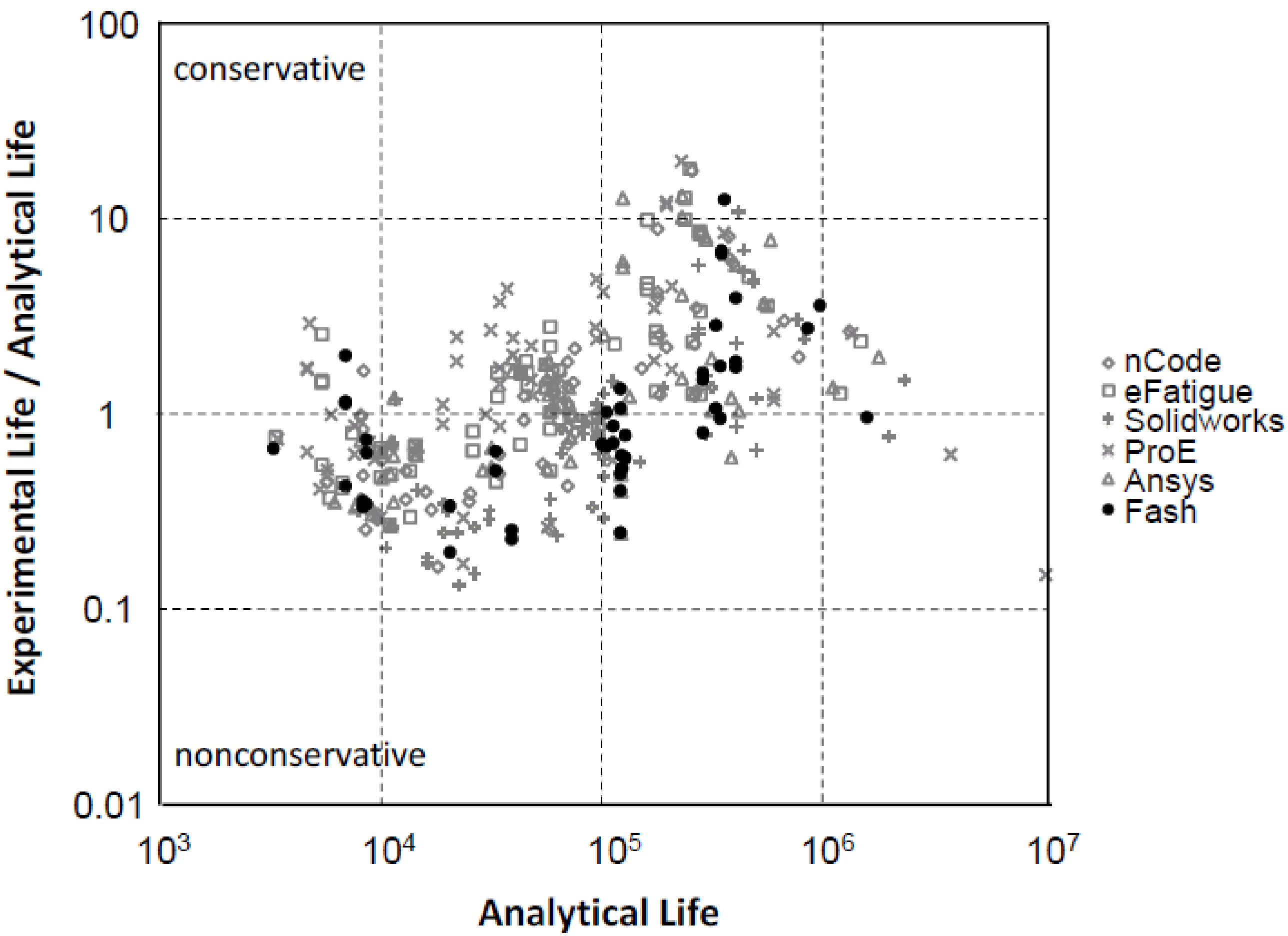
As modified by T. Cordes (15 April 2014)

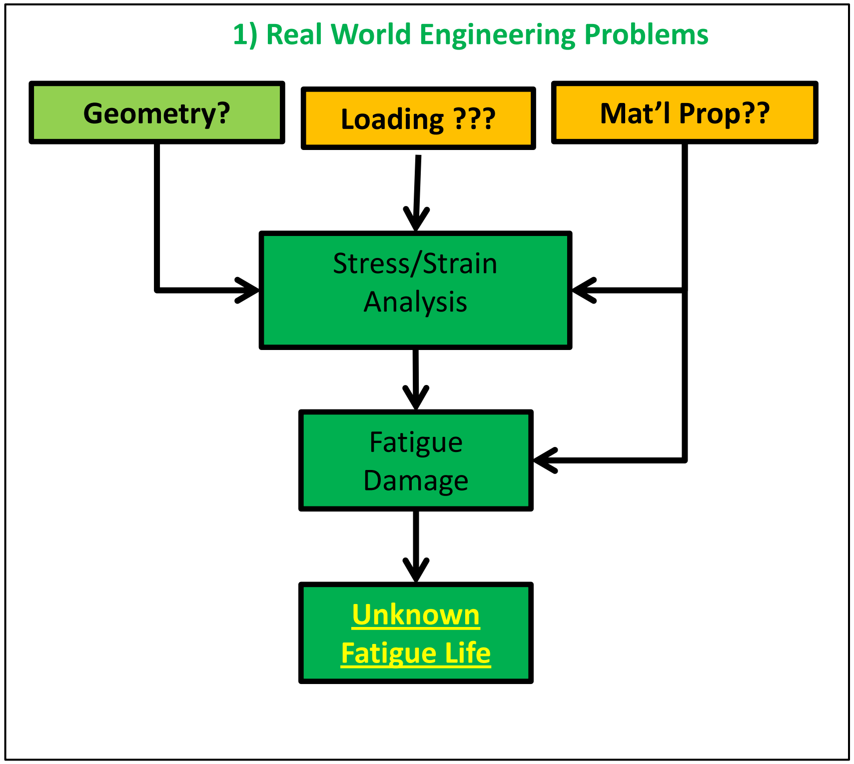
Total Fatigue Life: Crack Initiation and Crack Propagation

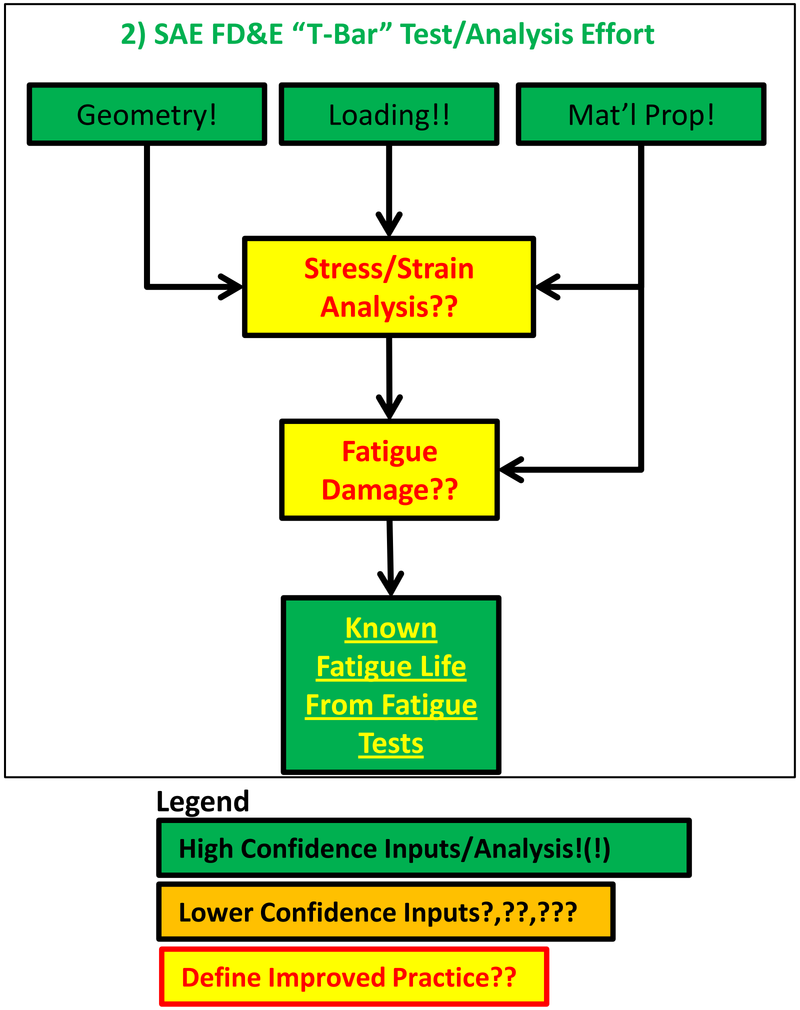
Previous SAE FD&E Analysis to Test Correlation Effort Results``

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

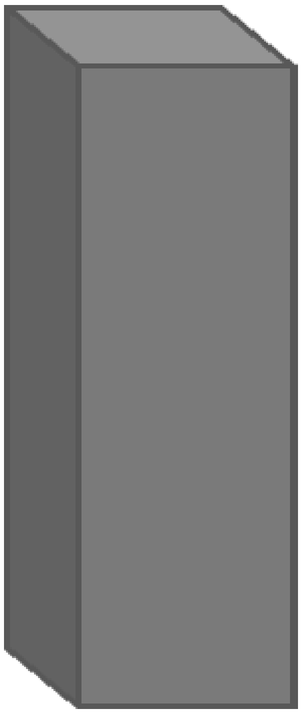




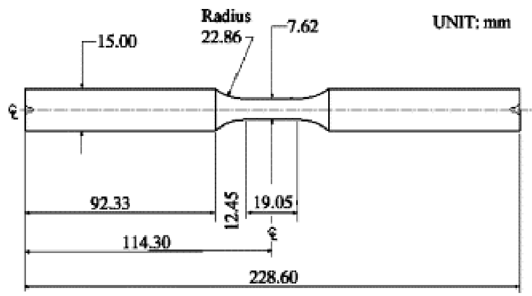
This effort is using "very well defined/controlled analysis inputs" to address an engineering problem to validate (or not) a potential "Total Fatigue Life Prediction Improved Practice"

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

Purchased "Enough" 4 A36 20ft HR bars



Microstructure, Chemistry & Hardness Sample



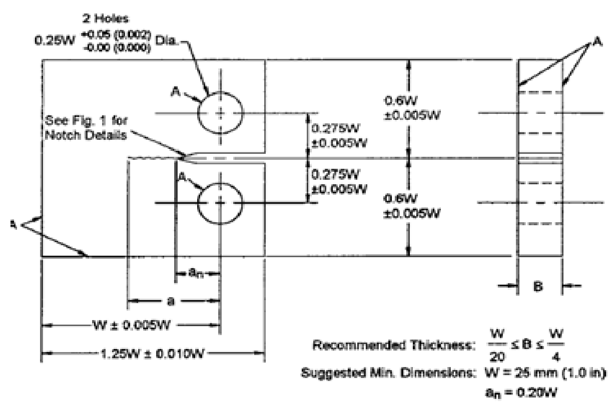
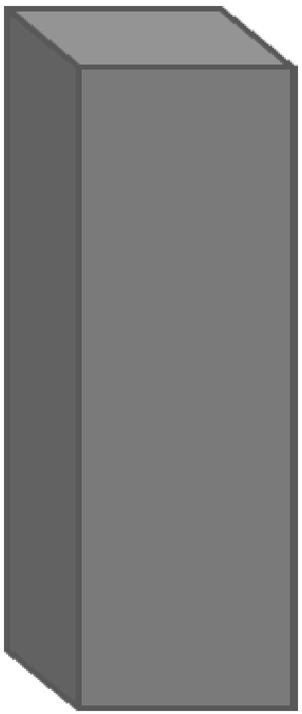
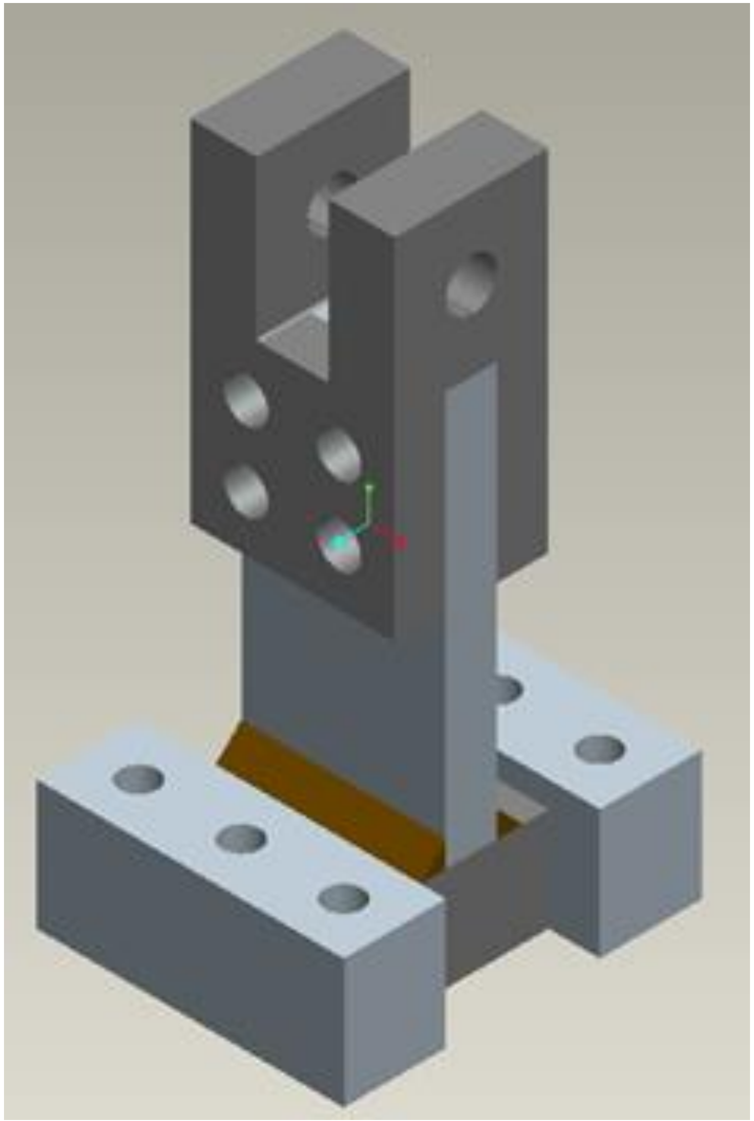


FIG. A1.1 Standard Compact-Tension C(T) Specimen for Fatigue Crack Growth Rate Testing
W=76.2 mm (3 in), B= 19.05 mm (0.75 in)

Total Fatigue Life: Crack Initiation and Crack Propagation Analysis

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

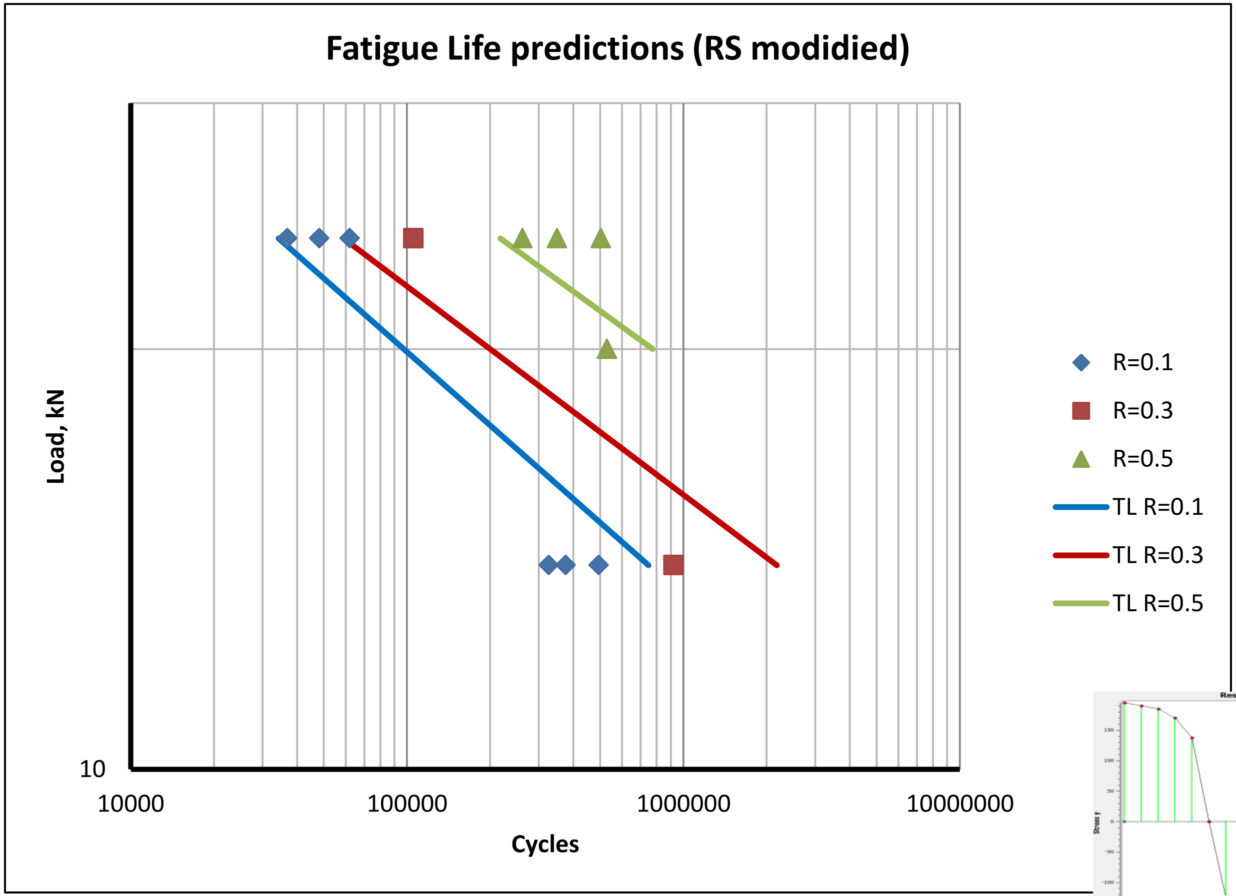


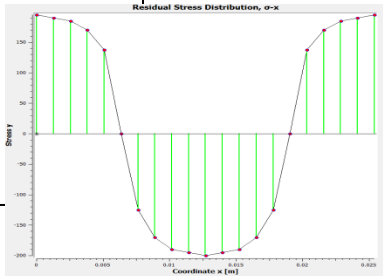


See Next Slide

Total Fatigue Life – Crack Propagation Analysis Includes Crack Initiation Analysis

FCG analysis using Total Life and RS modified



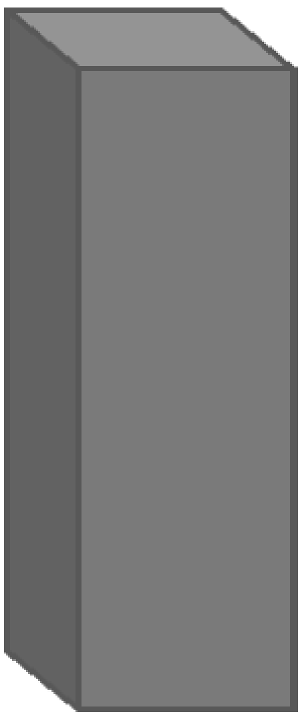


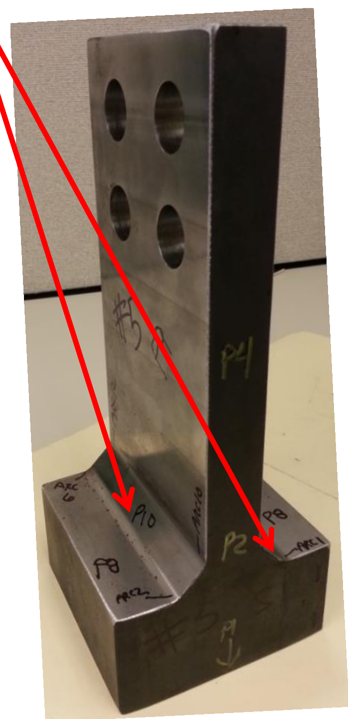
- Total life approach was run with initial semi-circular crack with a=b=ρ* until failure
- R=0.1, R=0.3, and R=0.5 were used
- L=24kN, L=20kN, and L=14kN were used
- Very similar results as for RS measured, slightly longer life in all cases

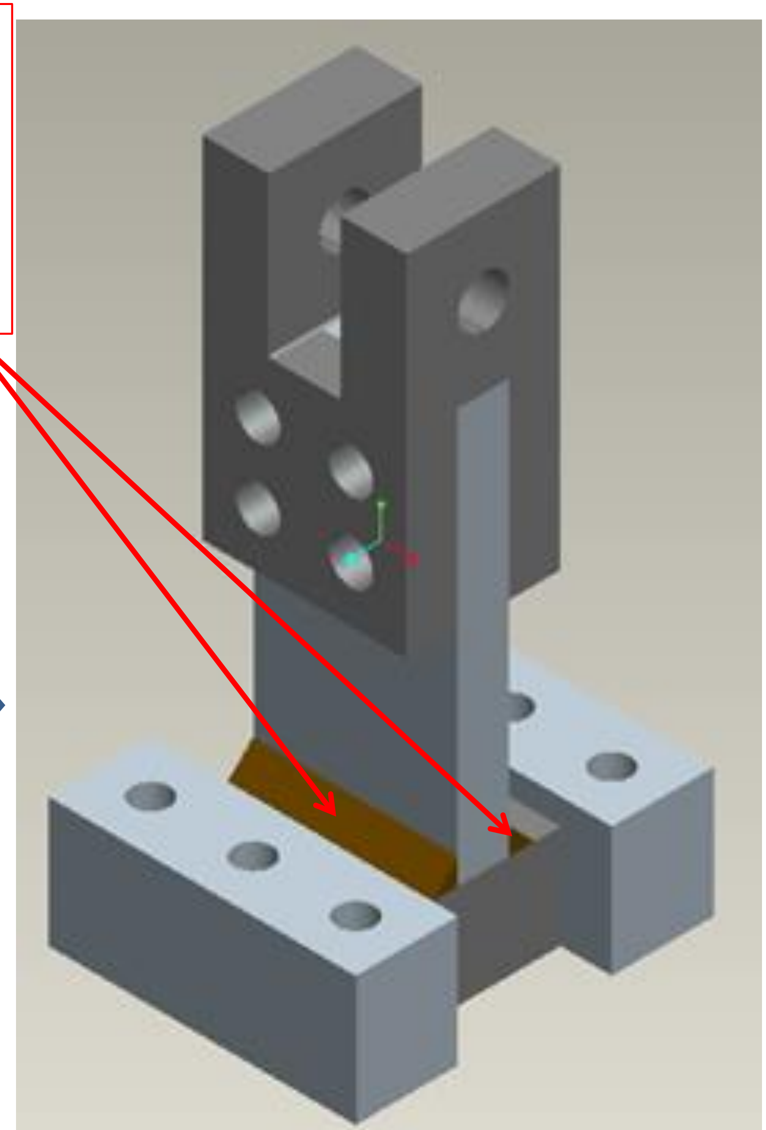
Machined

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

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

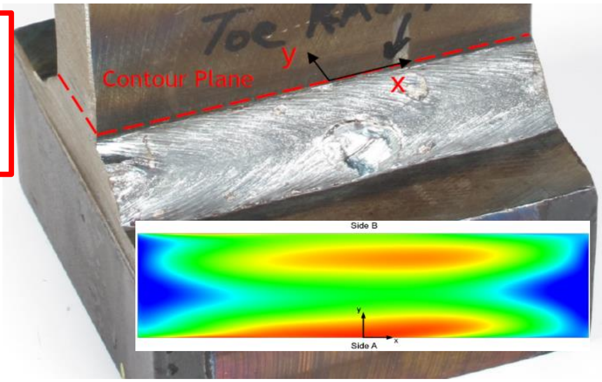
=

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

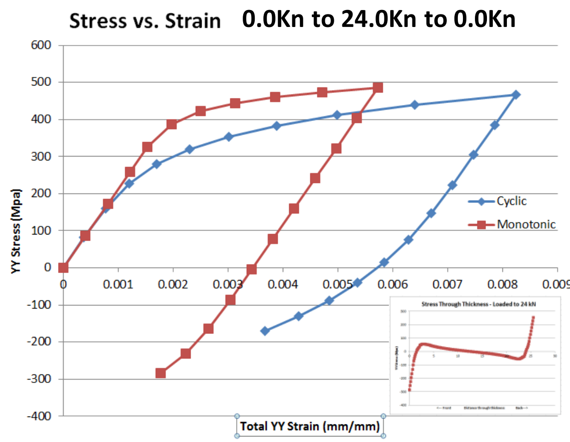
This presentation will focus on the "Machined Sample"

?

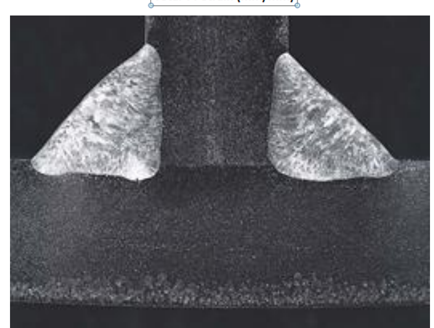
Residual stresses from welding

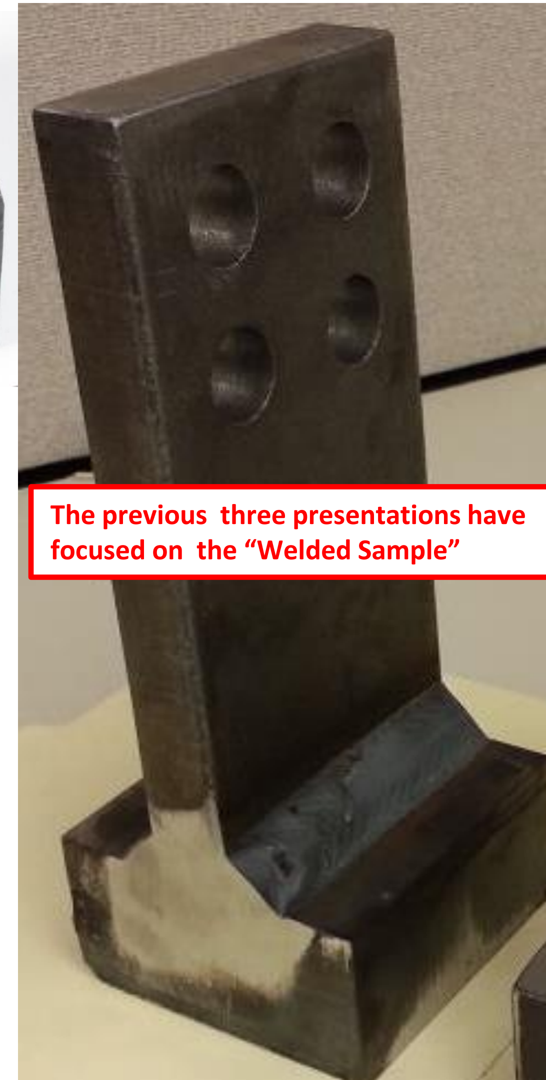


Residual Stresses from setup cycle applied <u>after residual stresses from welding</u>



Welded micro-structure influences

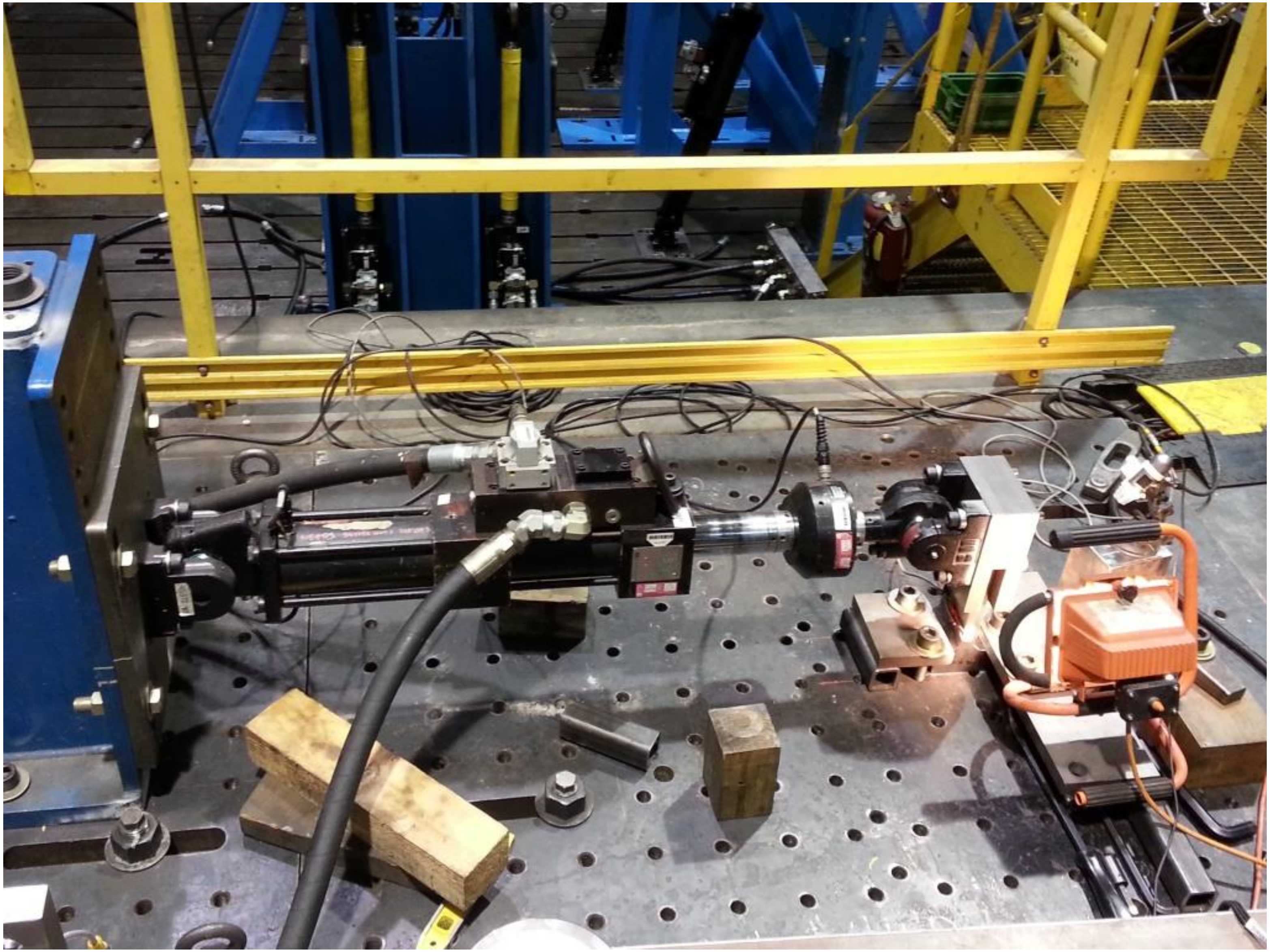




The previous three presentations have focused on the "Welded Sample"

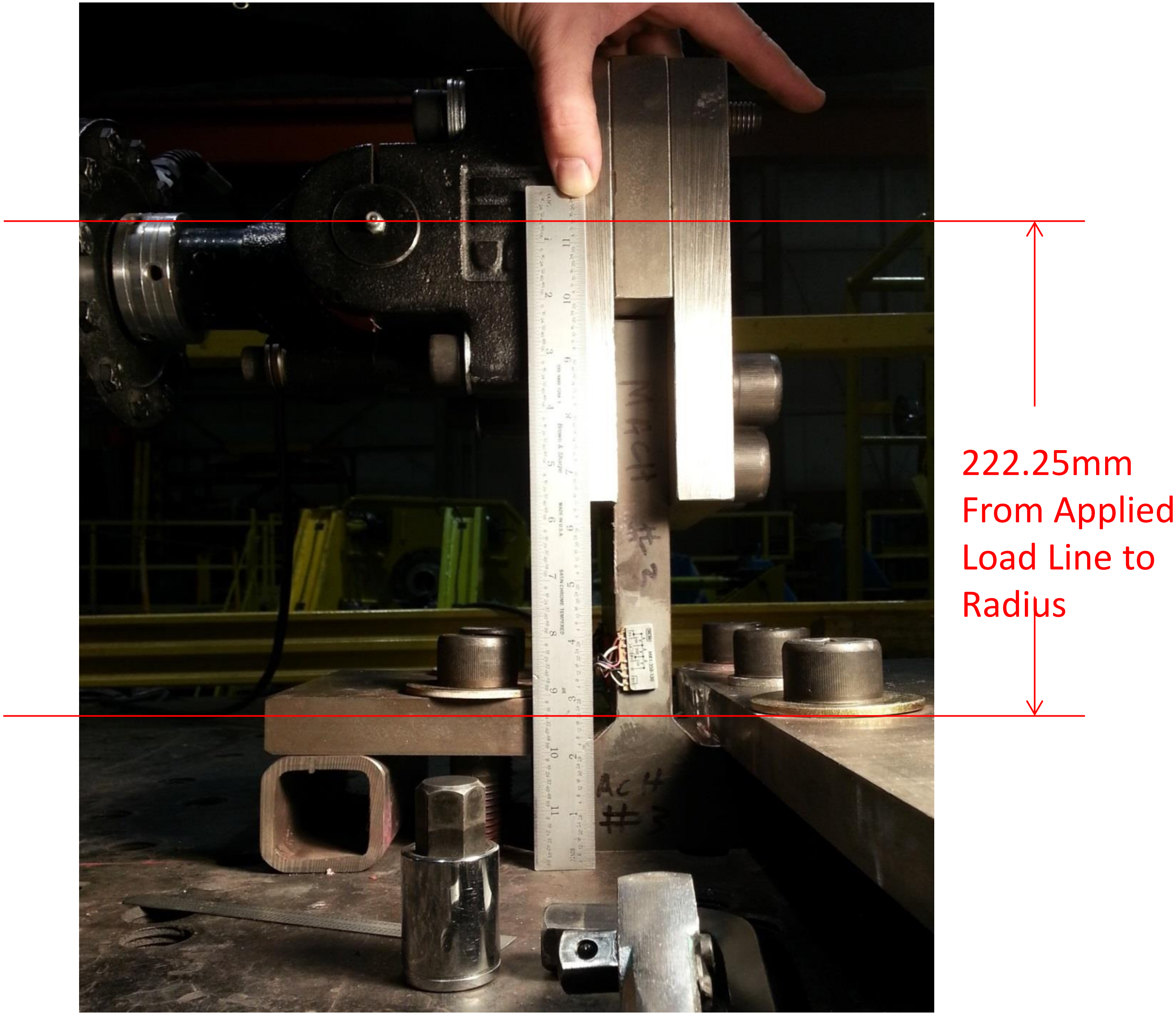
Total Fatigue Life: Crack Initiation and Crack Propagation Analysis

Specimen in Test Fixture



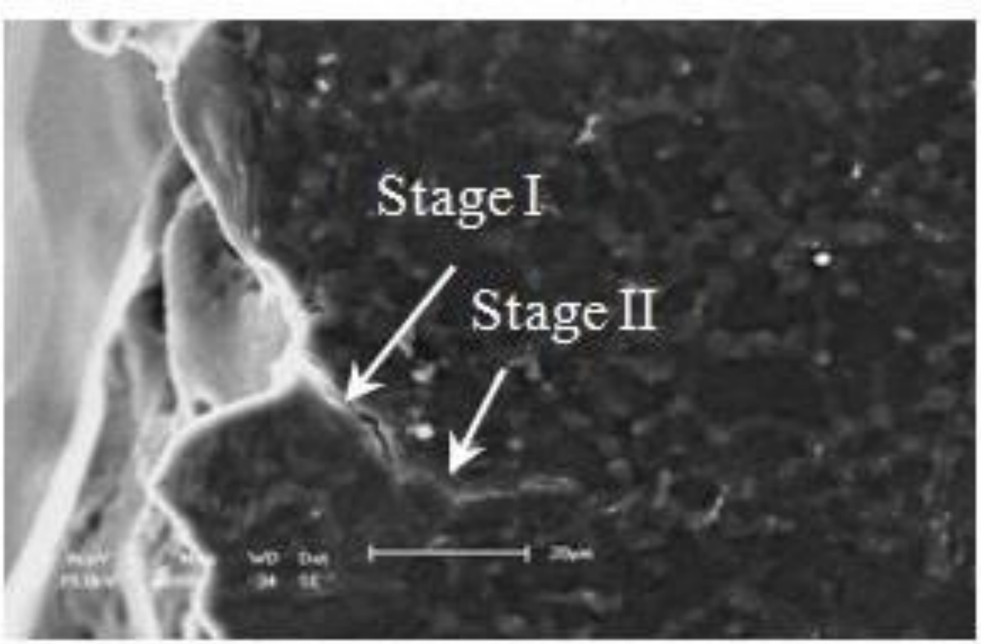
Total Fatigue Life: Crack Initiation and Crack Propagation Analysis

Specimen in Test Fixture/ for FEM Boundary Conditions



1. Overview of Effort
2. Machined Samples Analysis/Test Results Comparison Summary
3. 24Kn R=0.1(5,000 cycles)/0.5(40,000 cycles) Block Loading Machined Sample Detailed Analysis/Test Comparison
4. 24Kn Variable Amplitude Machined Sample Block Loading Analysis/Test Comparison – Issues?
5. Crack Initiation and Crack Propagation Analysis Methodology Background (If time allows)

Define CI and CP



Total Fatigue Life: Crack Initiation and Crack Propagation Analysis

Analytical/Experimental Results

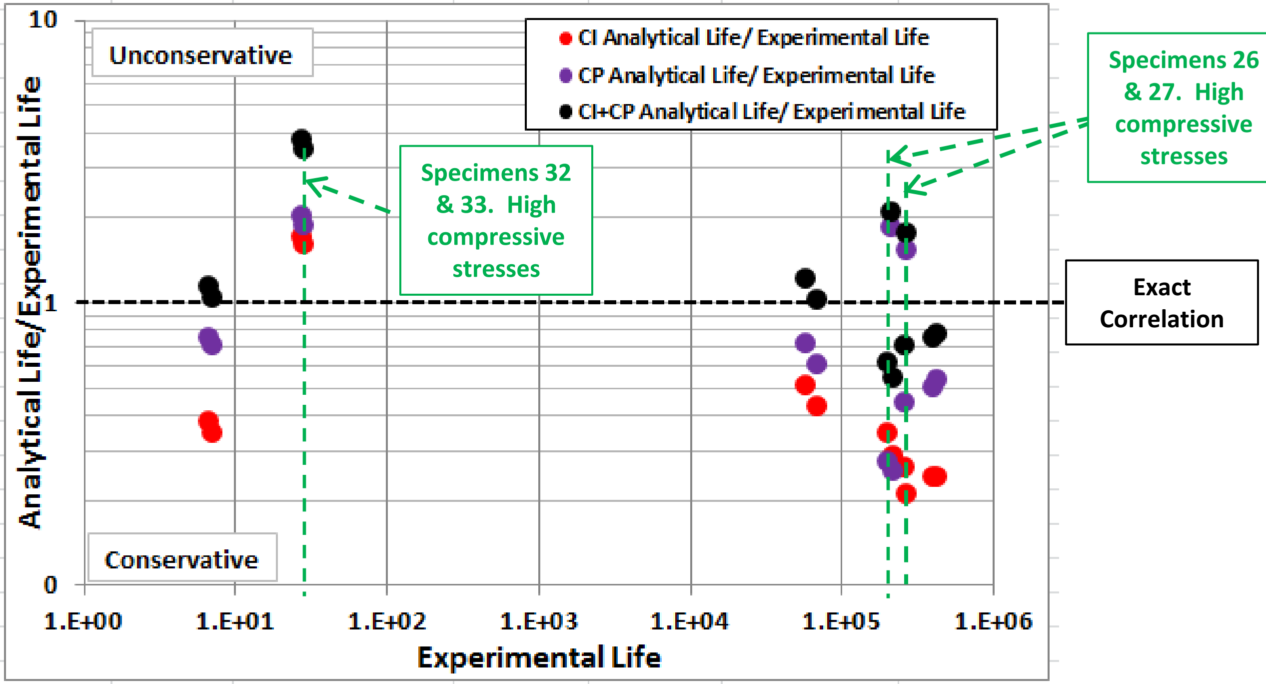
Specimen Number	Test Load Load Kn	Testing R Ratio Dimensionless	Max Stress Level Mpa	Max Strain Level ue	Setup Cycle R Ratio Dimensionless	Test Life (TL) Cycle Counter Cycles or Blocks	Test Life PV File Cycles or Blocks	Predicted CI Life Cycles or Blocks	Predicted CP Life Cycles or Blocks	Predicted CI+CP 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:

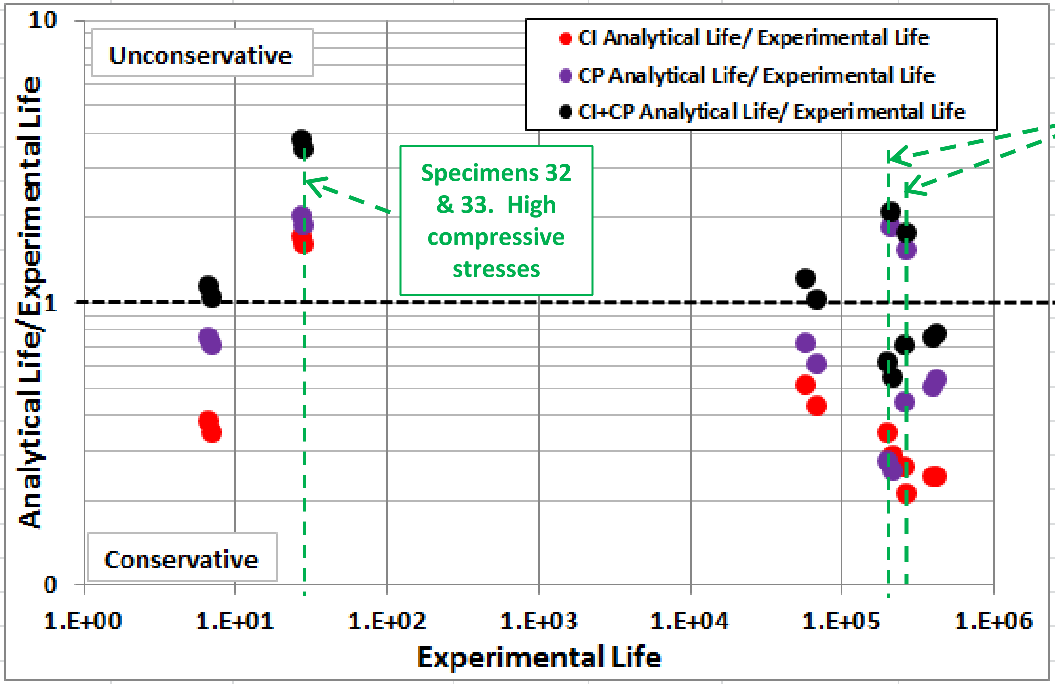
1) For the CI + CP fatigue life predictions, only peak valley histories with a lot of high compressive stress cycles vary significantly from a "correlation factor" of "1".

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



Specimens 26 & 27. High compressive stresses

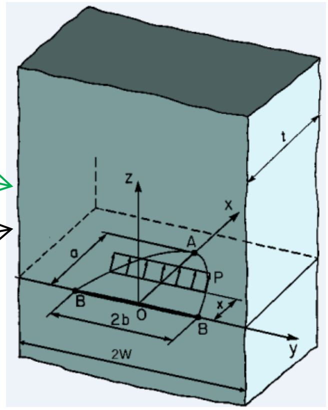
Exact Correlation

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.

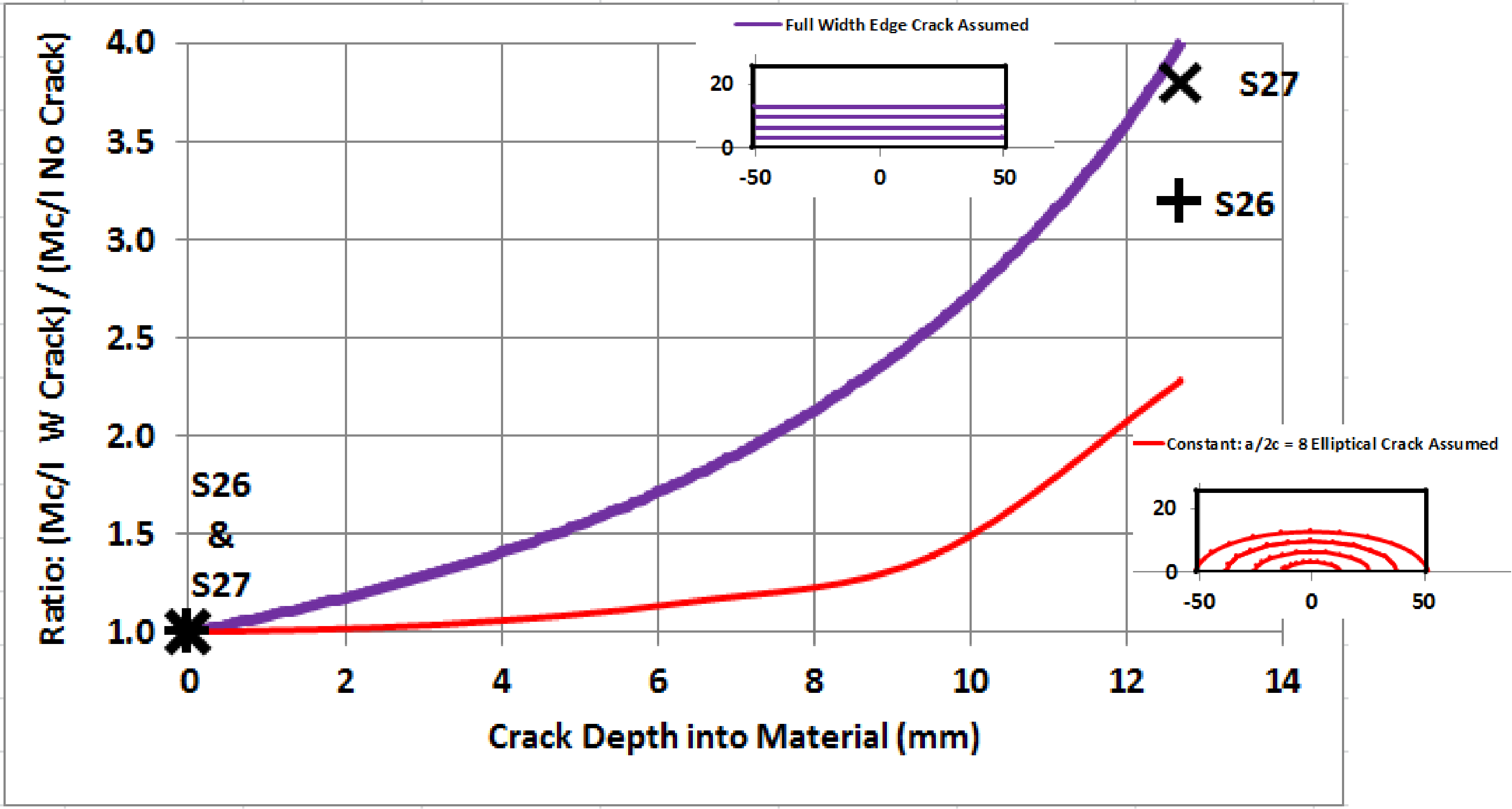
Specimens 26, 27, 32, and 33 "don't fit well" to SIF as used

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

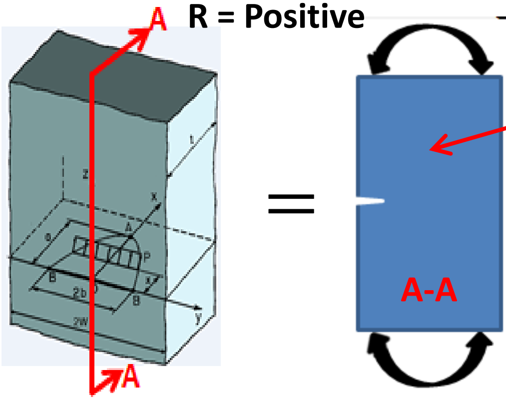


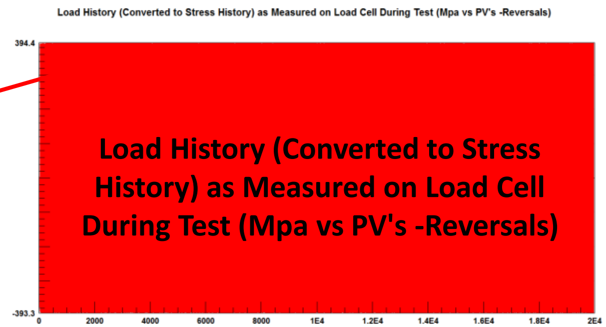
Further Description of Analysis Method: Only the compressive stress cycles in the peak-valley history where increased by this "linear empirical compressive stress correction trend". It calculated 1.00 times the stress at the start of the cycling and increased the stress at each subsequent compressive 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.

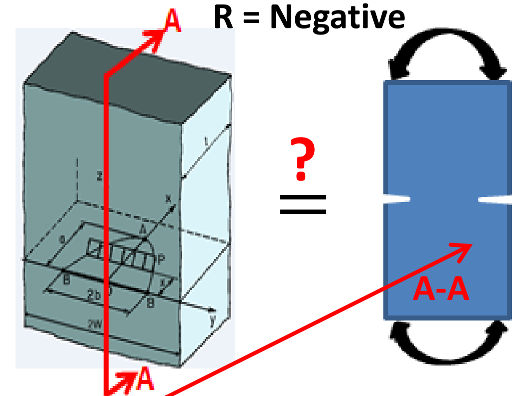
Total Fatigue Life: Crack Initiation and Crack Propagation Analysis

Empirical Compressive Stress Correction

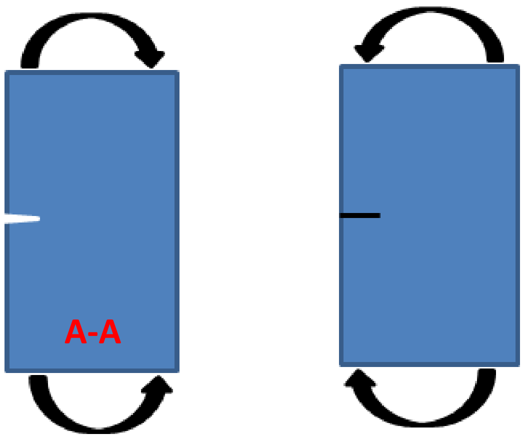
Caution: The technique shown below should be implemented within the software code as a function of a and c (b). Because that was not feasible it was simulated externally as a function of cycles (N)





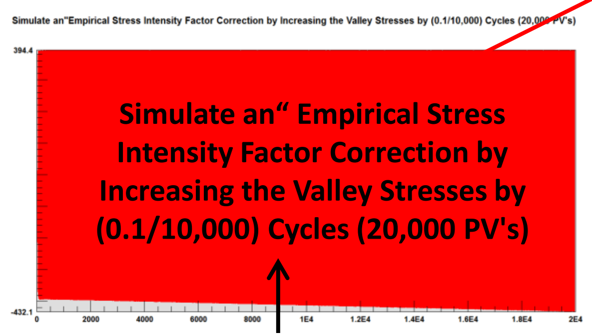


"Engineering is the art of being approximately right instead of exactly wrong"

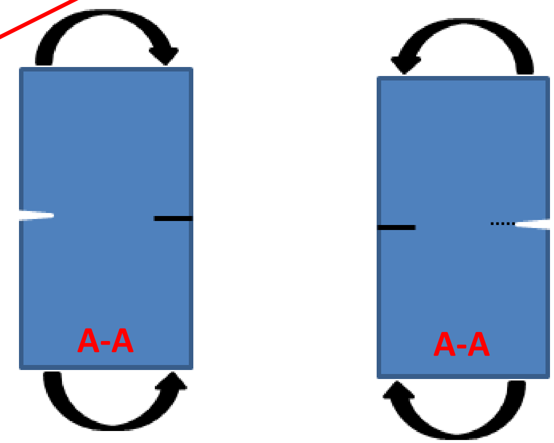


+S=M(c/I) Consistent with CG Stress Intensity Solution

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

-S=M(c/I) Not consistent with CG Stress Intensity Solution (c/I 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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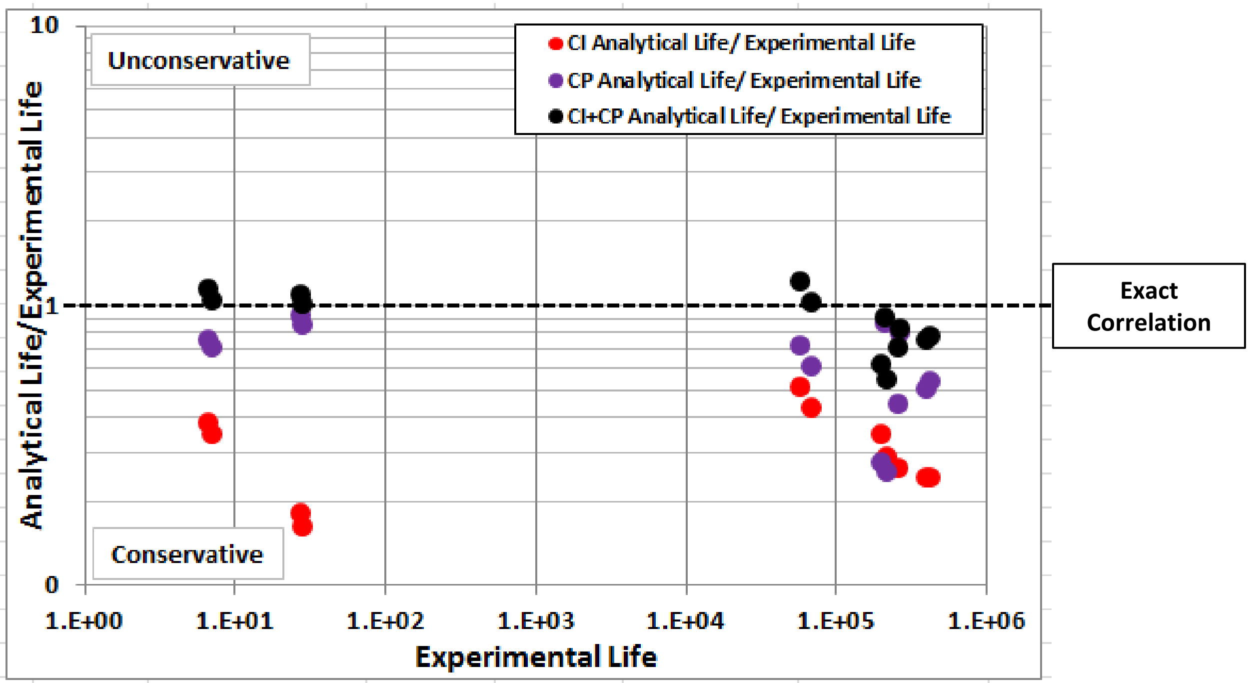
33	24	Variable Amplitude	870.44	4150	None	29.0	29.0	4.7	24.3	29.0	2.8	1.00

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



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4. **24Kn Variable Amplitude Machined Sample Block Loading Analysis/Test Comparison – Issues?**

5. **Crack Initiation and Crack Propagation Analysis Methodology Background (If time allows)**

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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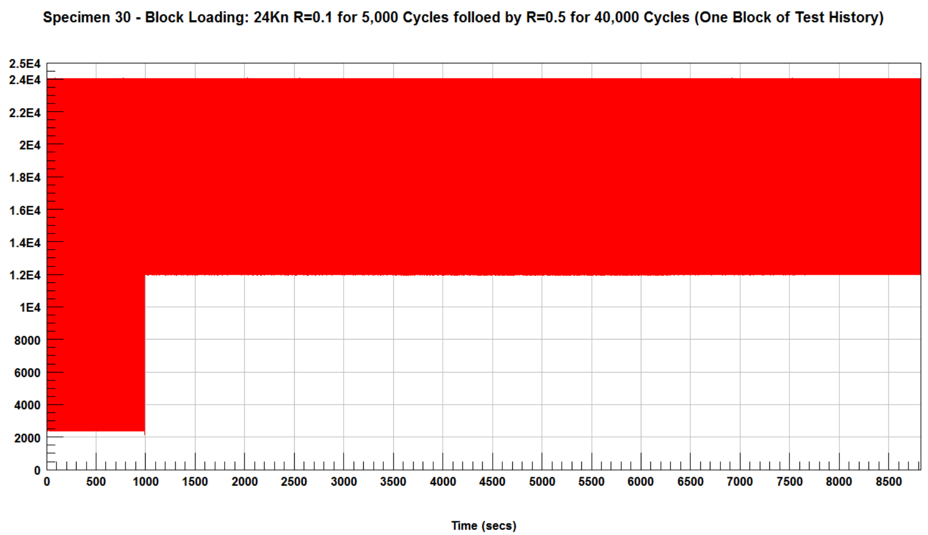
33	24	Variable Amplitude	870.44	4150	None	29.0	29.0	4.7	24.3	29.0	2.8	1.00

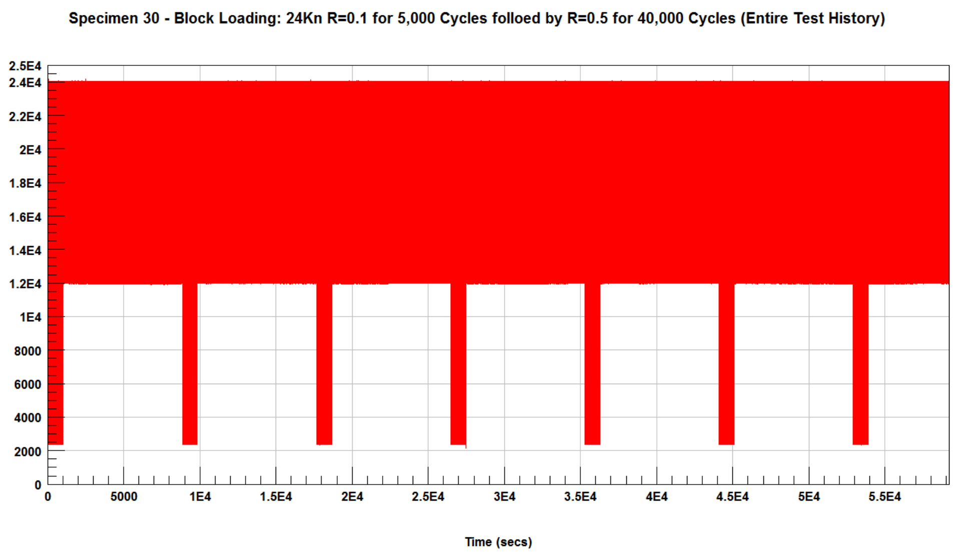
Note: *5,000 24Kn R=0.1 Cycles followed by 40,000 24Kn R=0.5 Cycles

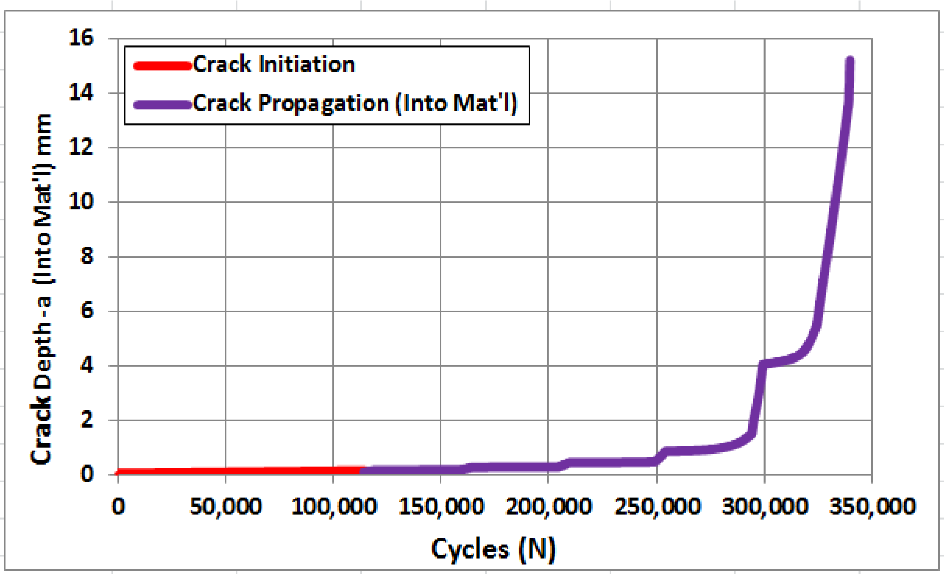
Note that this was one of the nine (out of thirteen) samples that needed no empirical compressive stress correction.

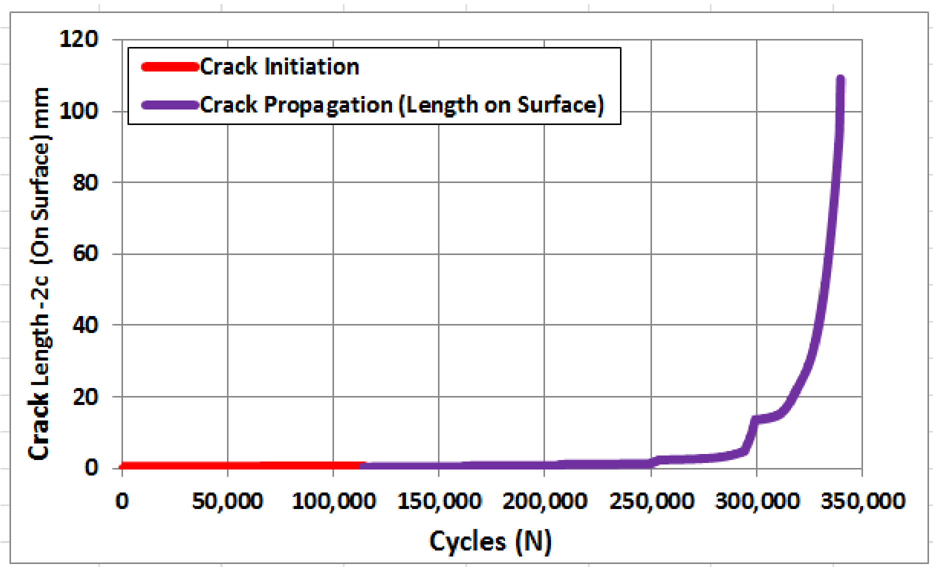
Total Fatigue Life: Crack Initiation and Crack Propagation Analysis

Analytical/Experimental Results (With Empirical Compressive Stress Correction)



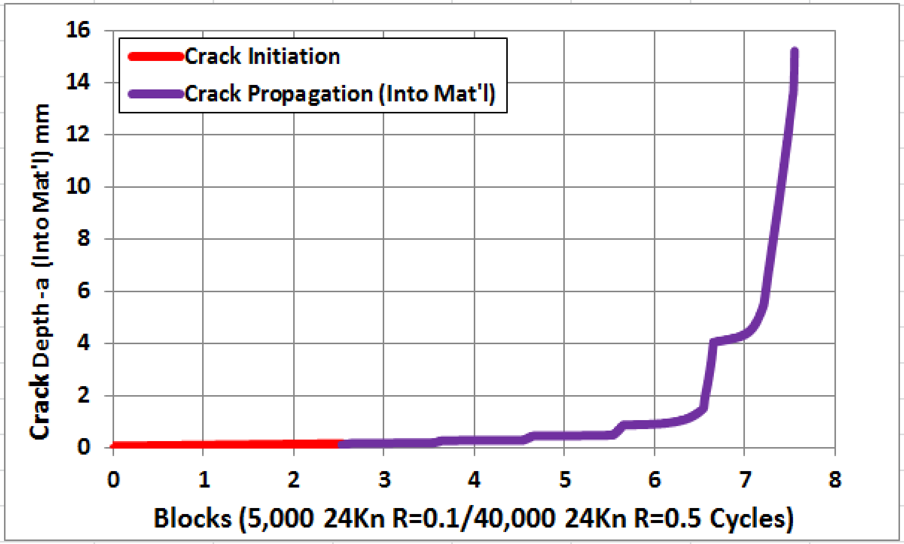


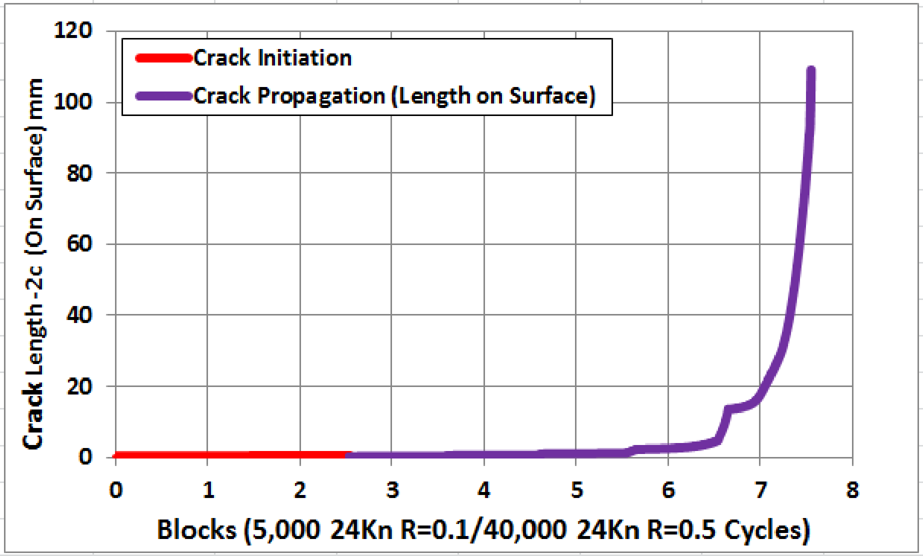


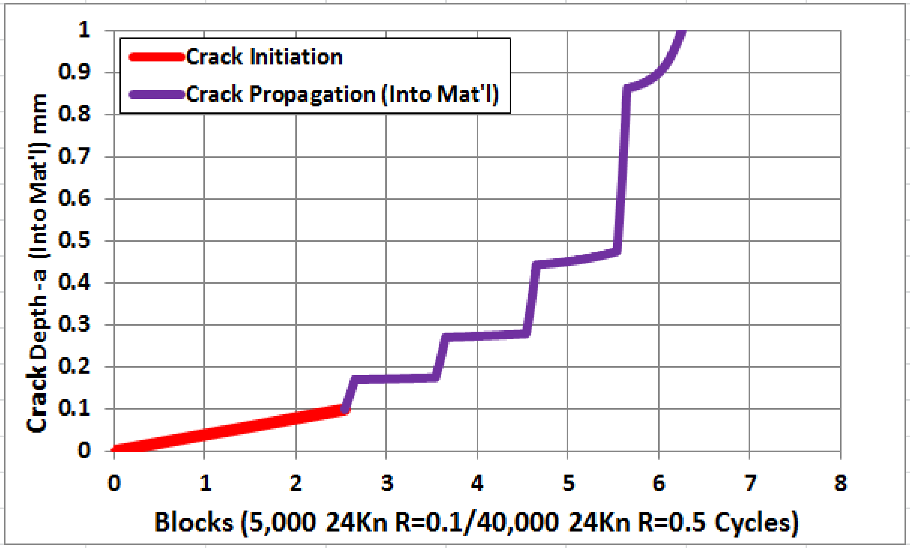


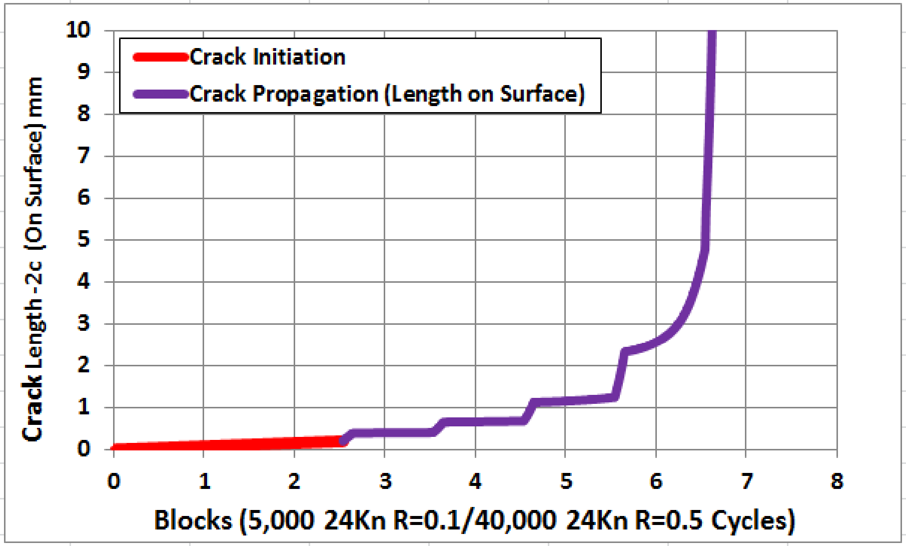
Total Fatigue Life: Crack Initiation and Crack Propagation Analysis

Analytical/Experimental Results (With Empirical Compressive Stress Correction)

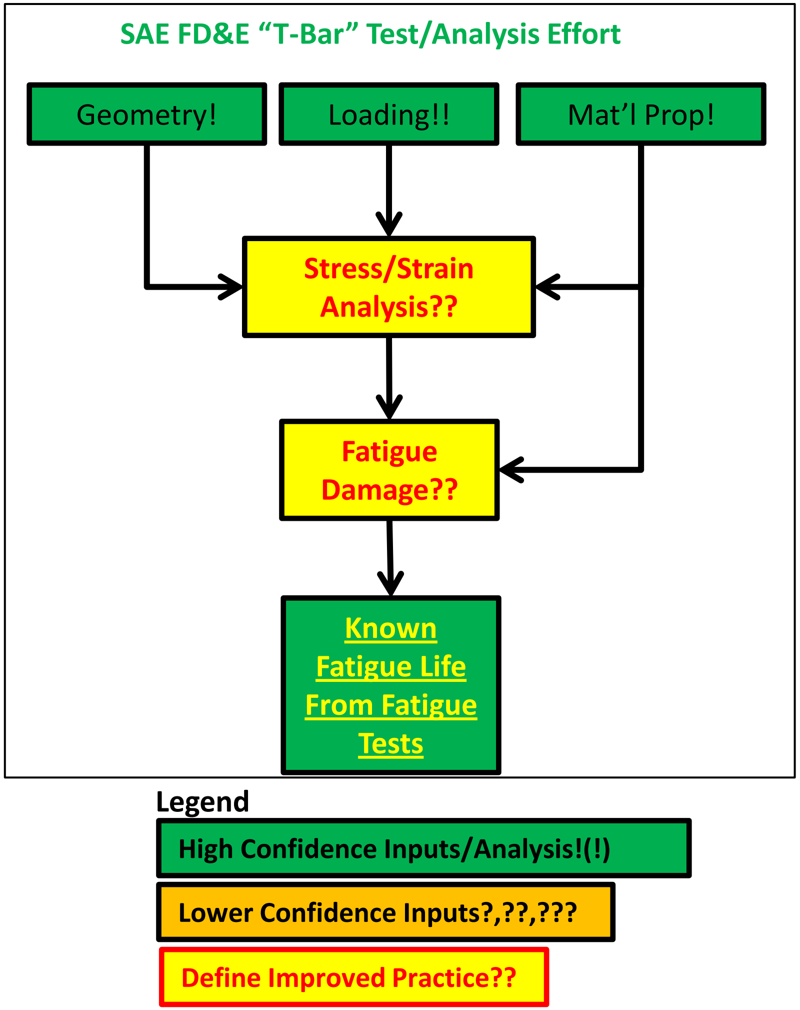








Total Fatigue Life: Crack Initiation and Crack Propagation

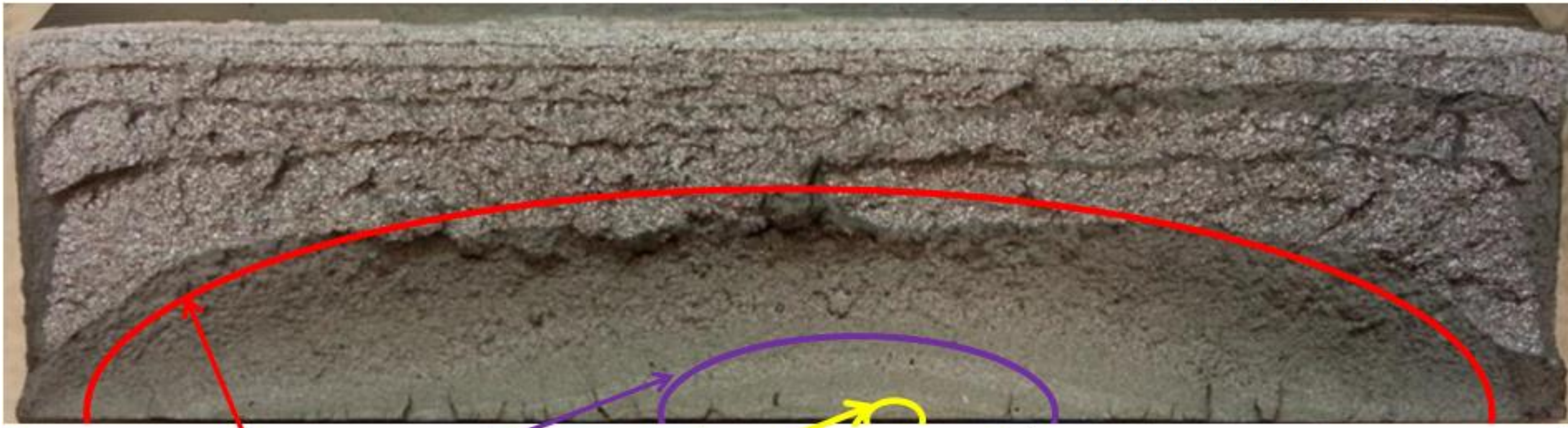


It would be very difficult to consistently stop a "crack initiation evaluation test" at a consistent crack size (and shape) when evaluating a "Life Prediction Improved Practice" because of the very shallow slope of the a vs N curve in that region. Attempting to do that would probably be interpreted as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

Total Fatigue Life: Crack Initiation and Crack Propagation Analysis

<u>Analytical Crack Growth Prediction Results vs Experimental Results</u>

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.

1. **Overview of Effort**

2. **Machined Samples Analysis/Test Results Comparison Summary**

3. **24Kn R=0.1(5,000 cycles)/0.5(40,000 cycles) Block Loading Machined Sample Detailed Analysis/Test Comparison**

4. **24Kn Variable Amplitude Machined Sample Block Loading Analysis/Test Comparison – Issues?**

5. **Crack Initiation and Crack Propagation Analysis Methodology Background (If time allows)**

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

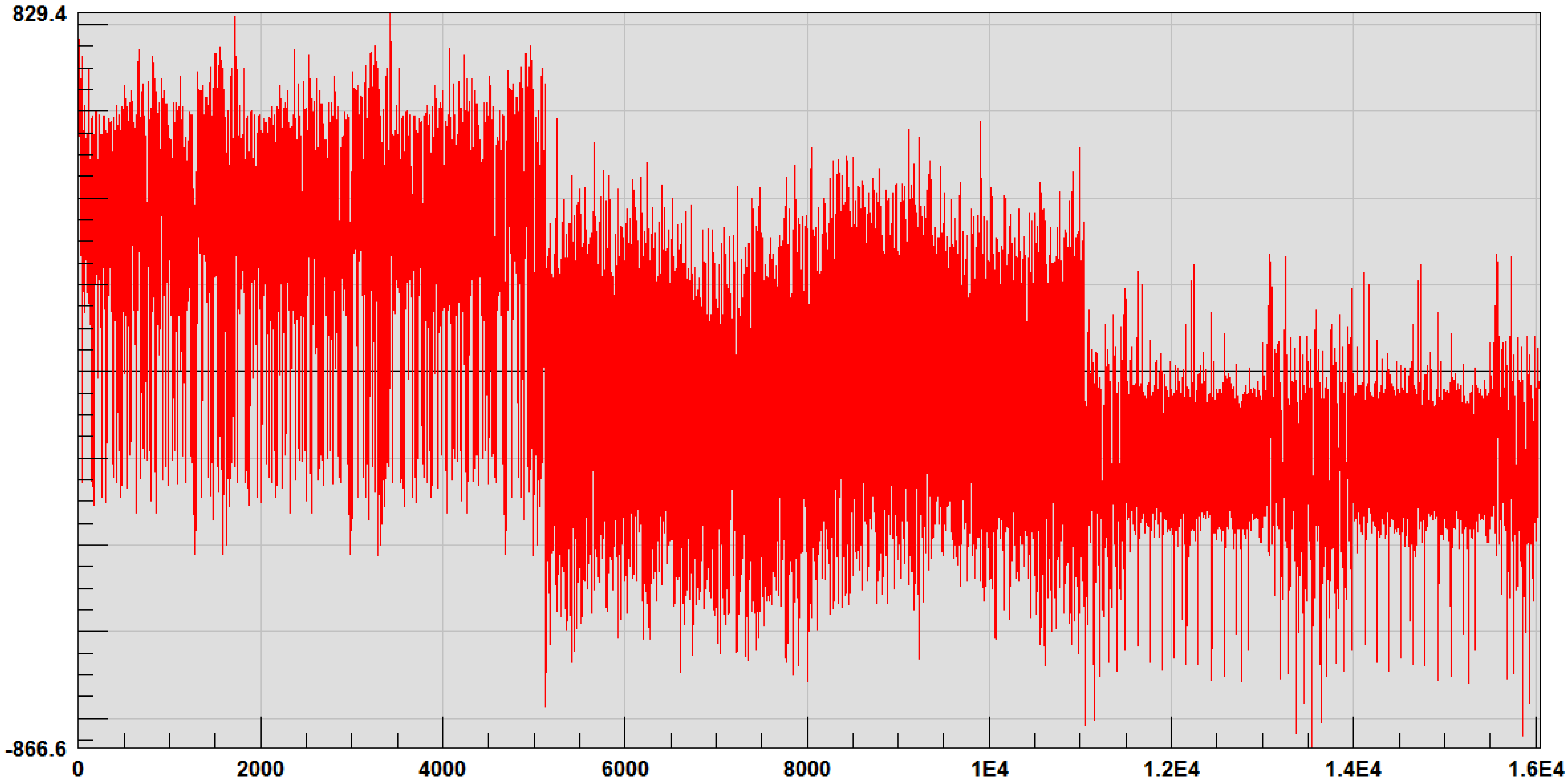
Note: *5,000 24Kn R=0.1 Cycles followed by 40,000 24Kn R=0.5 Cycles

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

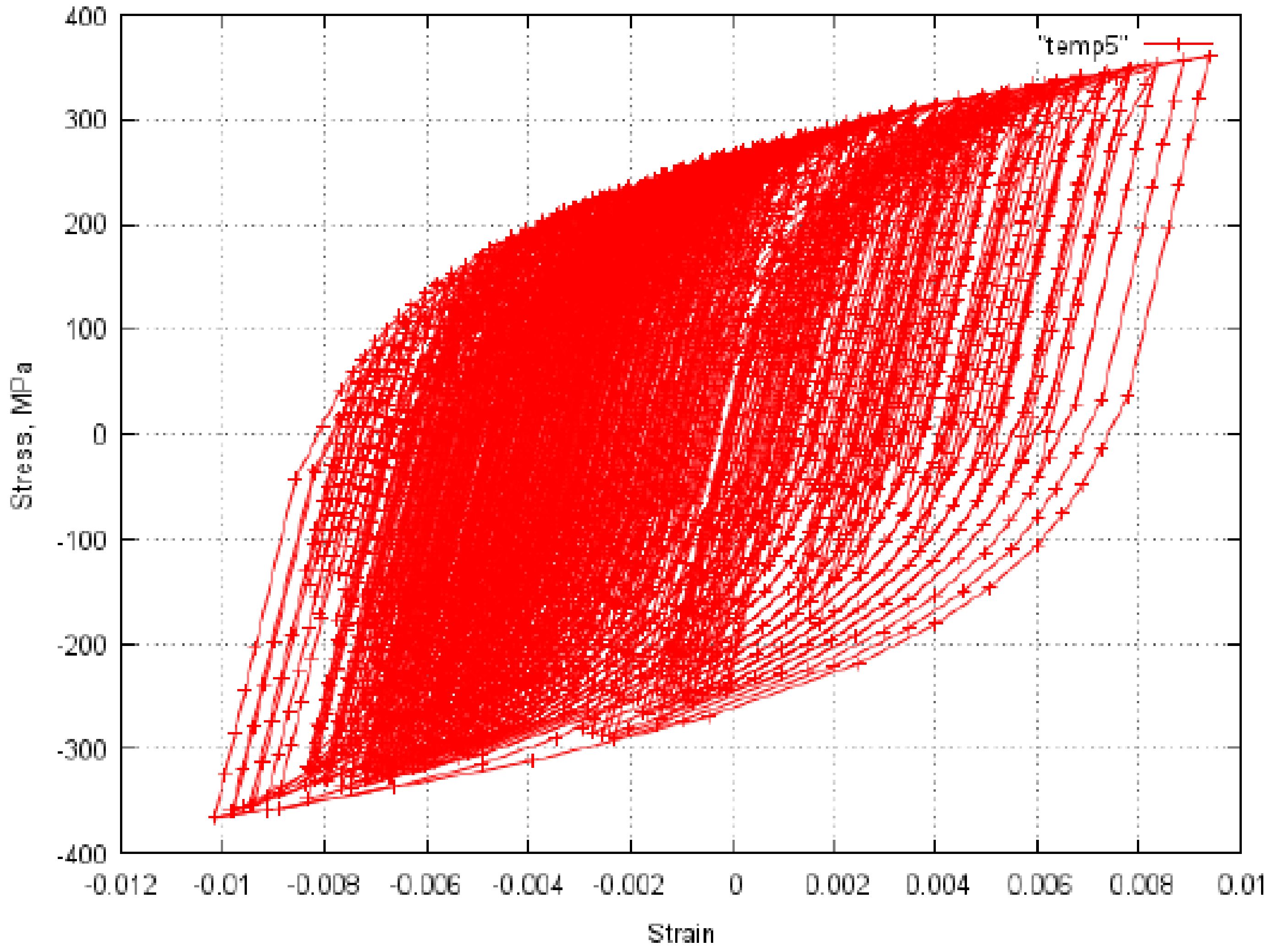
Analytical/Experimental Results

Variable Amplitude PV History = 3x SAE Transmission History+ 1x SAE Bracket History+ 2x SAE Suspension History



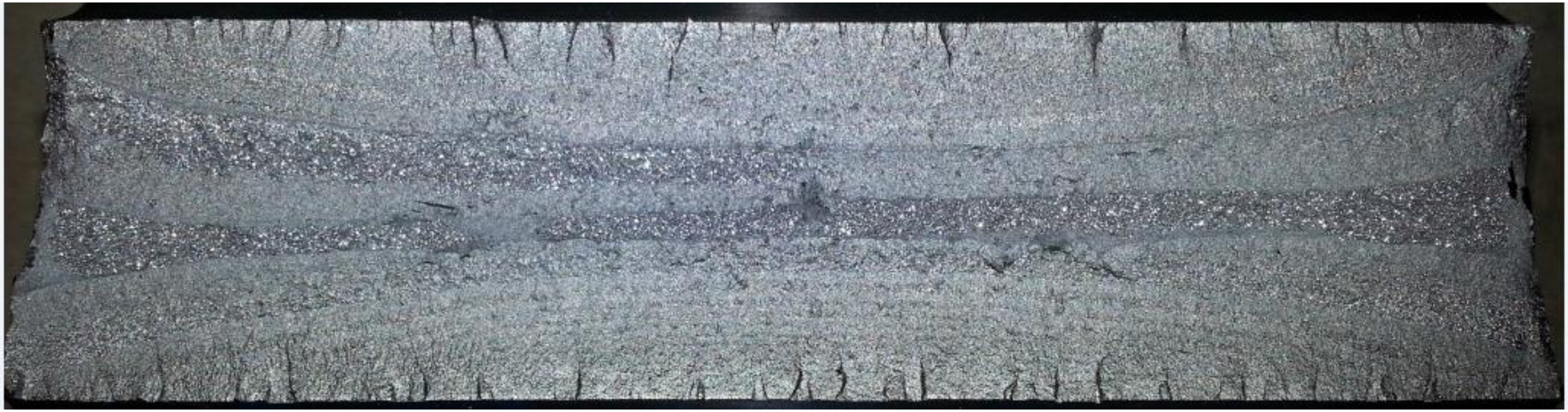
Analytical/Experimental Results

Local Stress and Strain Response:



Total Fatigue Life: Crack Initiation and Crack Propagation Analysis

Work Currently in Progress to Sort out Difference between Analytical and Experimental Results



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".

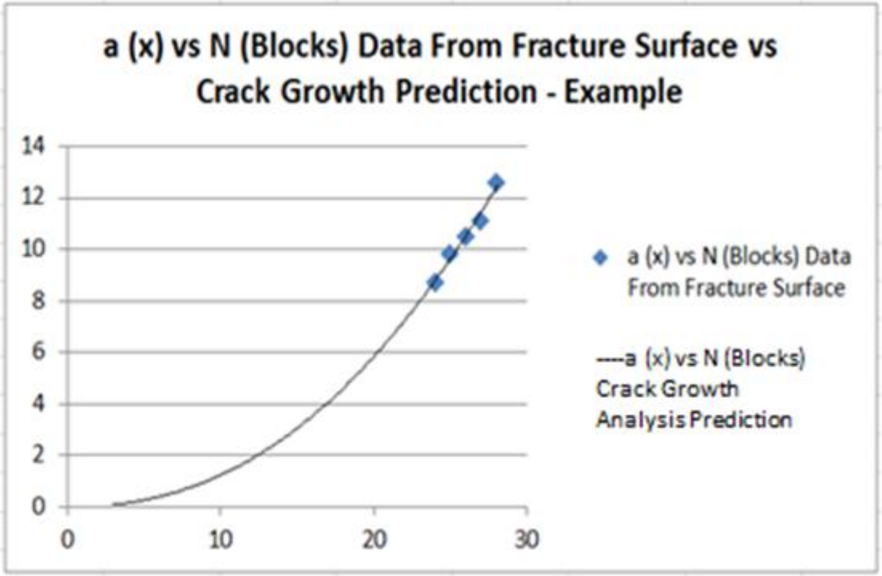
Please Provide the Table as Shown Below

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

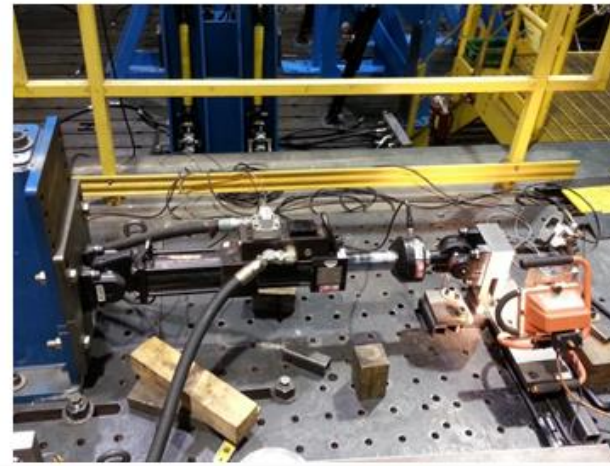
The SAE FD&E Committee Will Provide the Crack Growth Prediction and the Correlation as Shown Below

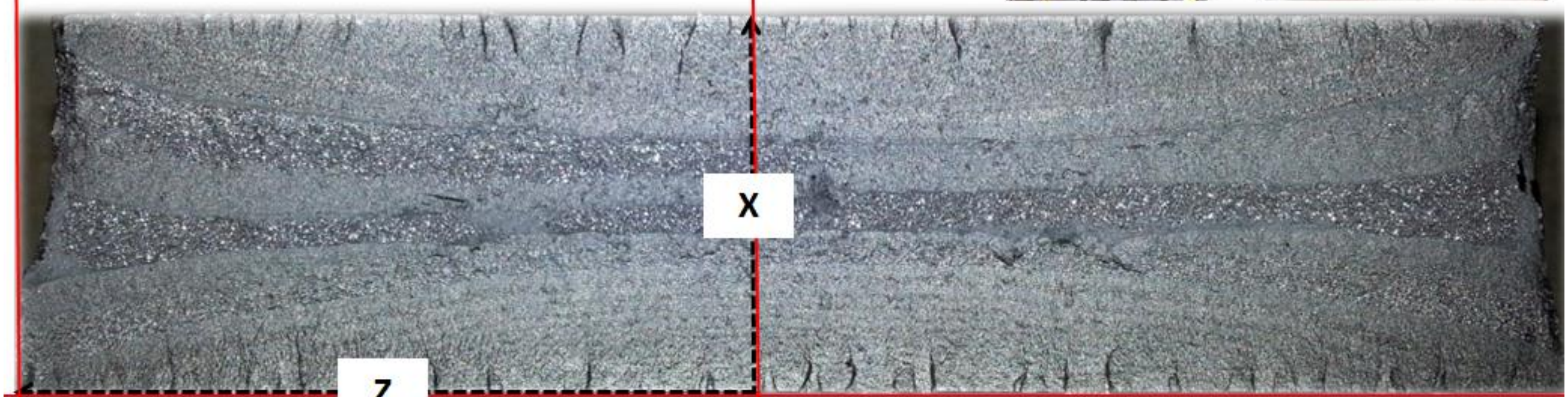


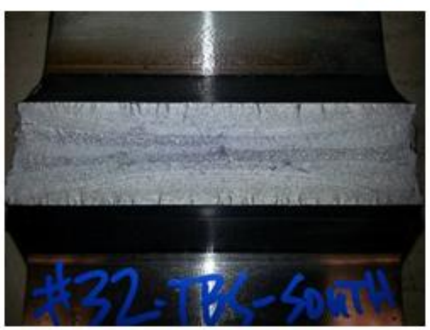
Total Fatigue Life: Crack Initiation and Crack Propagation Analysis

Plane c
on 25.4 mm
Surface

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



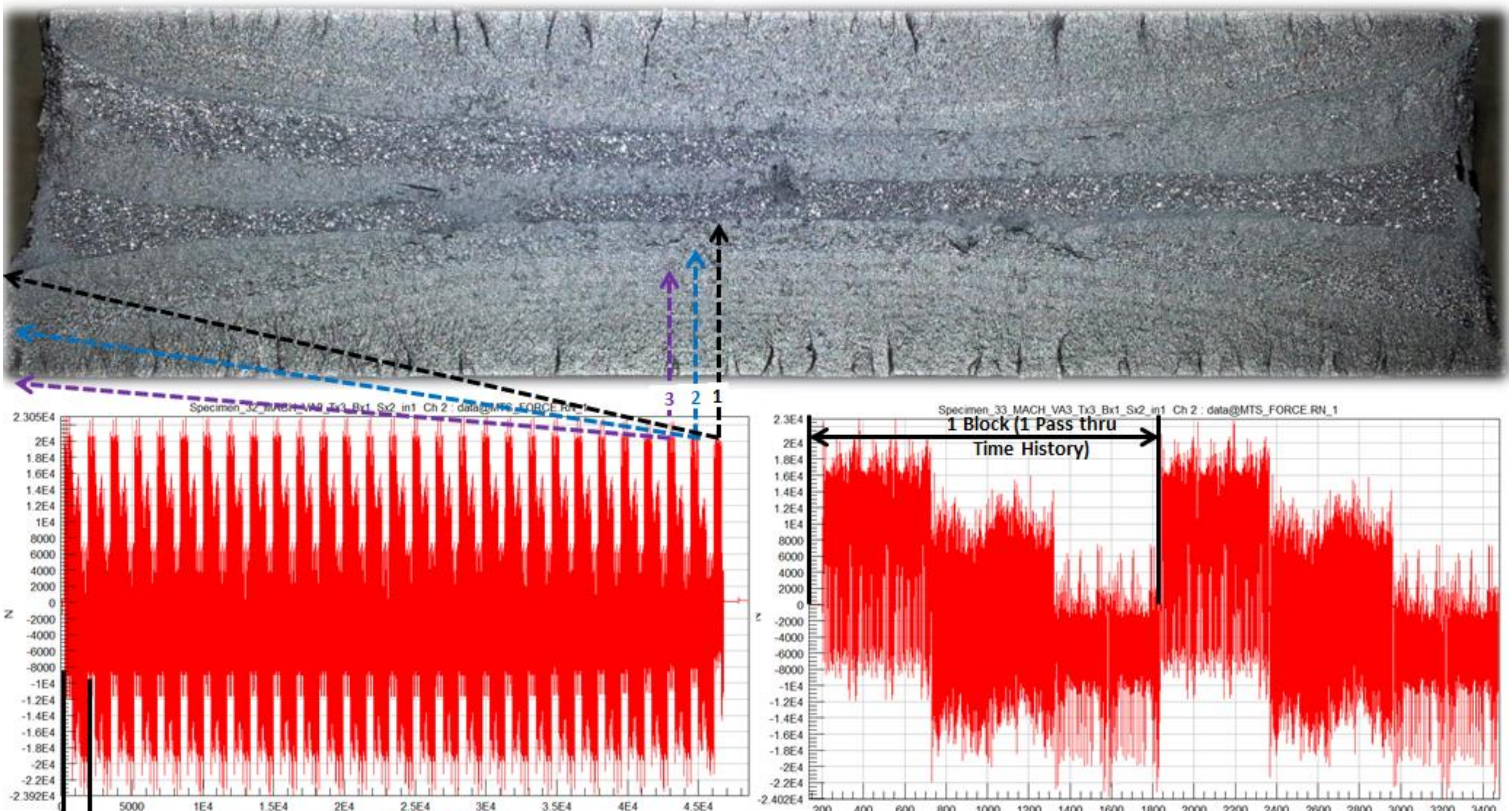




Origin
(0.0 mm, 0.0 mm)
(X,Z)

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
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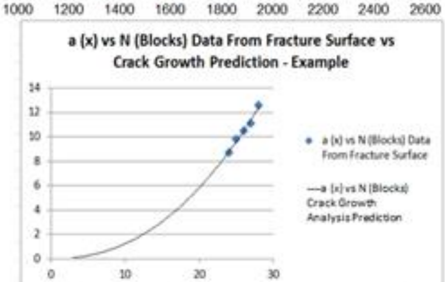
4	26	9.8	0	0	45.5
5	25	8.7	0	0	43.2
6	24	8.5	0	0	41.7
...	...	...	...	...	...
.....	.....	.....	.....	.....	.....

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



Thank You