Summary of Fatigue Life Testing and Analysis of the A36 T-Joint Specimens Machined and Welded Completed Todate

SAE FD&E Semi-Annual Meeting

Contributors: See Next Slide

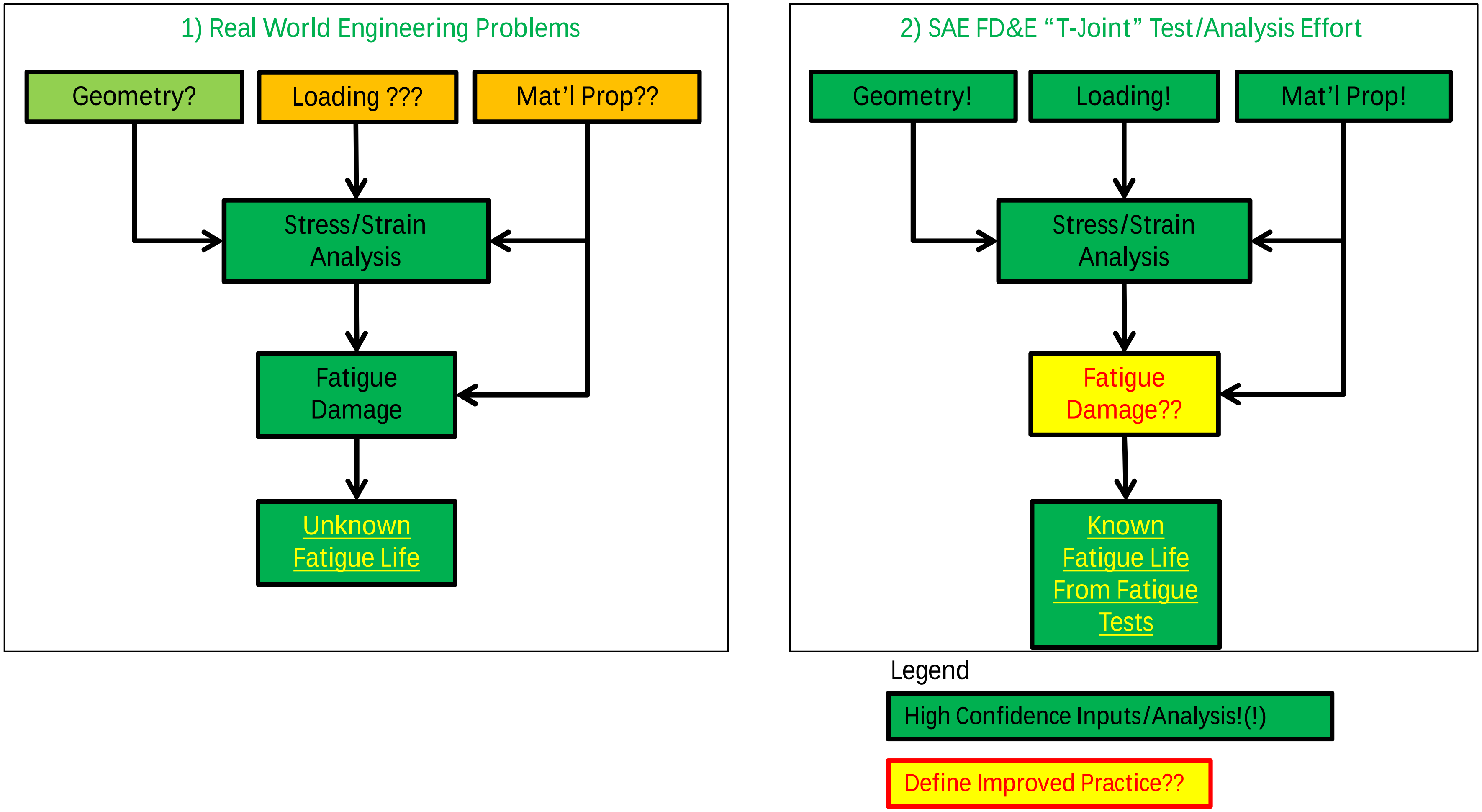
11 Oct 2018

Society of Automotive Engineering Fatigue Design and Evaluation Committee (SAE FD&E) A36 T-Joint Effort Participants/Contributors

- SAE FD&E Committee Administrative/Leadership: Chad Kerestes (Previous Chairman)-CAT, Casey Gales (Chairman)-JD, James Patterson (Vice Chairman)-Hendrickson
- Machined & Welded T-Joint Component Fatigue Tests: Ryan Blodig, Eric Norton, Mike Lister, and others-JD; Tom Cordes, Dan Lingenfelser-nCode
- T-Joint Component Finite Element Analysis: Hayley Brown-CAT, Peter Huffman-JD, Matt Campbell-Kansas State
- Generate Strain-life & Crack Growth Data/Strain Measurements: Phil Dindinger - Element Materials Technology; Jonathan Pickworth – Trilion Quality Systems
- Residual Stress Distribution Measurements: Perry Mason, Doug Hornbach and Paul Prevey - Lambda Technologies; Adrian DeWald-Hill Engineering
- Striation (Marker Band) Measurements: N. Jayaraman, Doug Hornbach and Paul Prevey - Lambda Technologies; Stephen Horstemeyer, Nima Shamsaei,-Mississippi State
- Welded T-joint Component Fabrication & Test Direction/Support: Eric Johnson-JD.
- Providing the Steel for the Preceding Contributions: Mary Wickham-CAT
- Funding for Some of the Preceding Contributions: Steve Haeg-MTS and Brian Dabell-nCode
- T-Joint Component Fatigue Life Predictions and Correlation to Test Data: Al Conle-University of Windsor; Semyon Mikheevskiy, Sergey Bogdanov and Grzegorz Glinka-University of Waterloo; Tom Cordes, Andrew Halfpenny-nCode
- Residual Stress Subcommittee: Casey Gales (Subcommittee Chairman), Eric Norton, Vipul Shinde, Rakesh Goyal-JD; David Griffith, Justin Mach, Chad Kerestes, Lingyun Pan, William Ulrich, Hayley Brown, Narendra Singh, Randy Peck, Timothy Vik-CAT; Matthew Campbell-Kansas State; Steve Haeg-MTS, John Goldack-Carleton University, Stephanie Swanson-Hendrickson
- Welded T-joint Component (2nd Round of Welded Components) Fabrication and Test Direction/Support: Eric Norton, Brandon Evans, and Casey Gales-JD.
- And any other participants and contributors: who may have been inadvertently overlooked in the preceding list.

“By participating in organized efforts the committee provides a forum within which members can work together in a synergistic manner to advance the state of the art in structural durability.”	“Through the years, members have found that the more they participate in the Committee activities, the more they grow in the area(s) of their particular involvement.”
From: Multiaxial Fatigue of an Induction Hardened Shaft (AE28) - Editors: Tom Cordes and Kevin Lease	

Total Fatigue Life: Crack Initiation and Crack Propagation

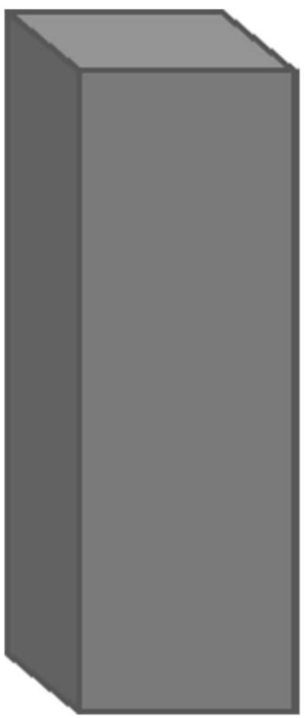


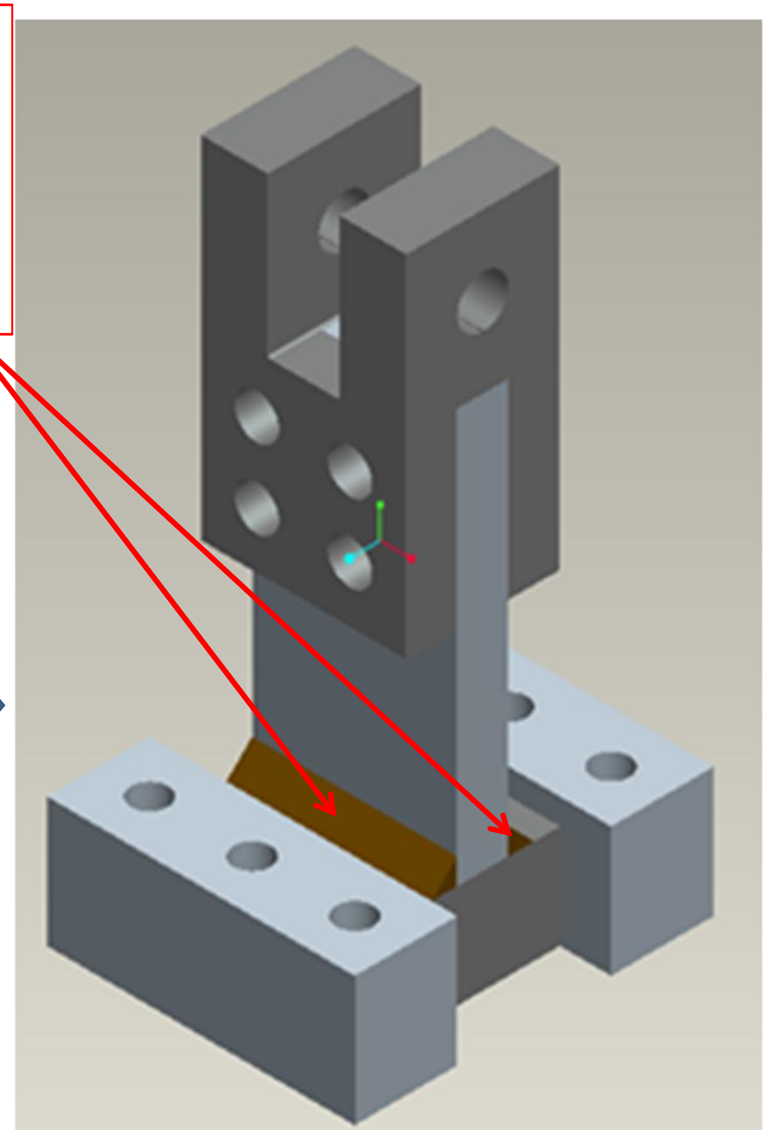
This effort is using “very well defined/controlled analysis inputs” to address an engineering problem to validate (or not) a potential <u>“Total Fatigue Life Prediction Improved Practice”</u>

Total Fatigue Life: Crack Initiation and Crack Propagation…Info

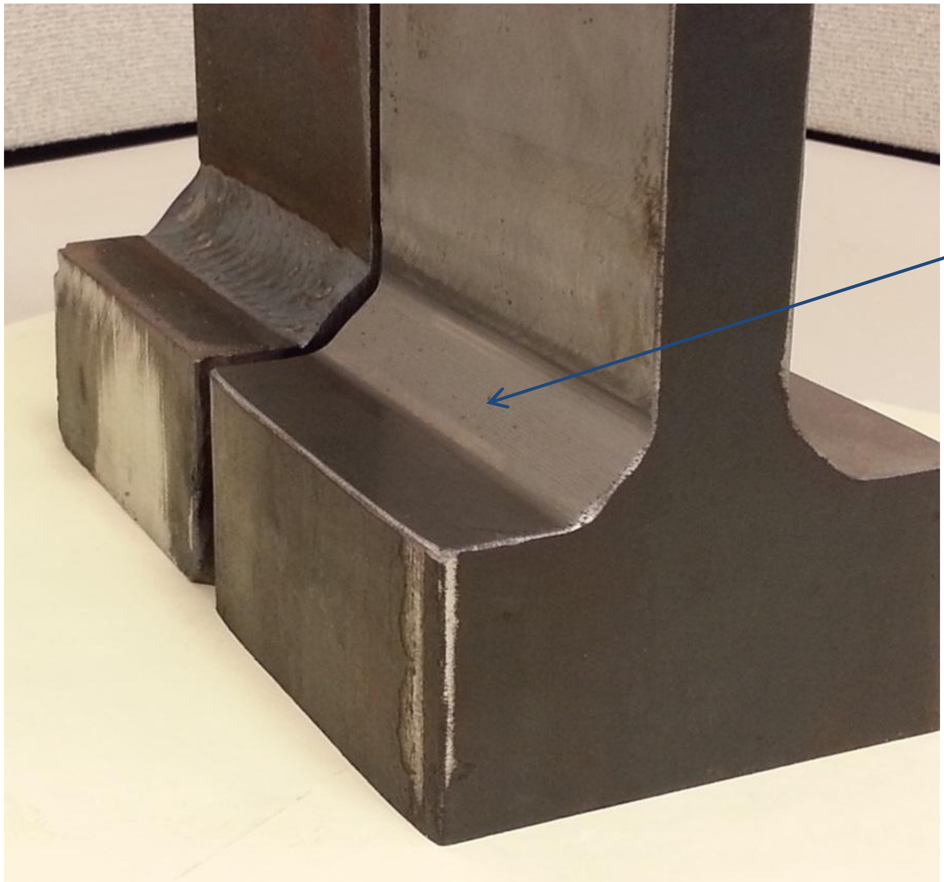
Machined
Specimen Configuration and Test Fixture/FEM Boundary Conditions

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 /analysis from these samples relative to the test/analysis results from the welded samples, will confirm (or not) assumptions like “can we use the base material properties when analyzing welded structures”, etc.

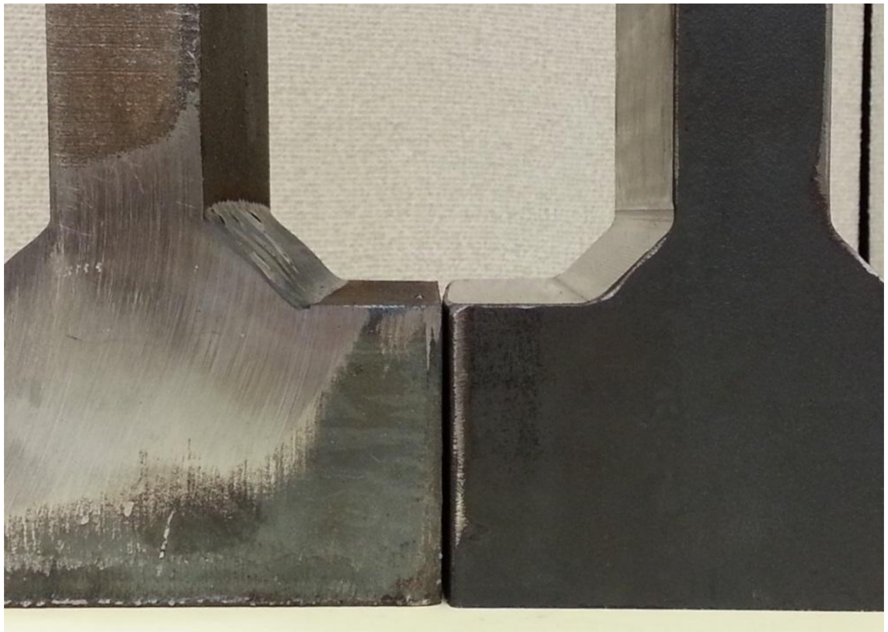




Welded and Machined Specimens



Machined T-Joint Replicates
Welded Specimen Geometry



T-Joint Test & Analysis Overview

- Test Log, 1st Round Welded and Machined Specimens
- Test Set Up
- Specimen Photos / Loading Histories
- RPC Iterations / Variable Amplitude Load History Files
- Fatigue Life Analysis
- 2nd Round Welded Specimens
- Residual Stress Measurements
- Questions / Comments

Test Log – Machined Specimens, Constant, Block, & Variable Amplitude Loading

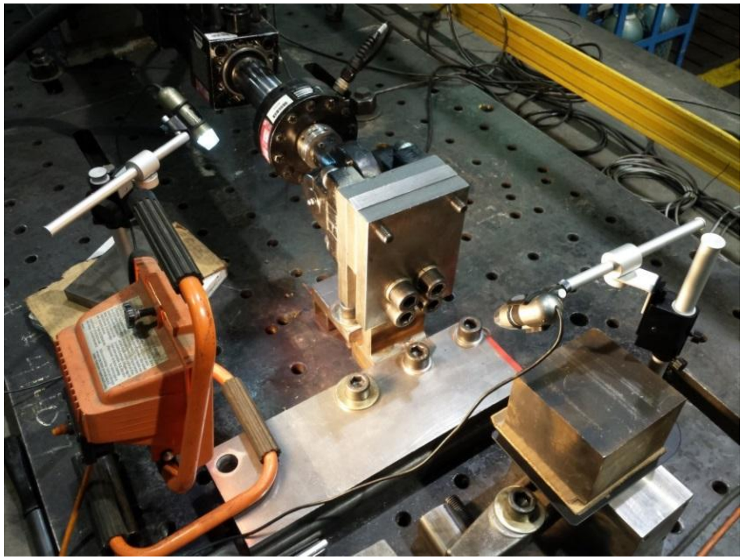
Specimen	Designation	Load (kN)	R Ratio (P_{min} / P_{max})	Cycles	Notes
19	MACH1	24	0.1	58481	Failure
23	MACH5	24	0.1	70011	Failure
22	MACH4-A	24	0.5	2471943	Run out
22	MACH4-B	24	0.3	266012	Failure
25	MACH7	24	0.3	218671	Failure
35	MACH12	24	0.3	200464	Failure
20	MACH2-A	14	0.1	3495011	Run out
20	MACH2-B	18	0.1	411745	Failure
24	MACH6	18	0.1	424431	Failure
26	MACH8	10.8	-1	214765	Failure
27	MACH9	10.8	-1	271951	Failure
29	MACH10_VA1	24	0.1	326135	Repeat Block (5k cycles @ R=0.1, 40k cycles @ R=0.5)
		24	0.5		
30	MACH11_VA2	24	0.1	301938	Repeat Block (5k cycles @ R=0.1, 40k cycles @ R=0.5)
		24	0.5		
32	MACH_VA2_TBS	Variable	Variable	28 Full Blocks	Repeat Time History, Trans x 3, Brkt x 1, and Susp x 2
33	MACH_VA3_TBS	Variable	Variable	29 Full Blocks	Repeat Time History, Trans x 3, Brkt x 1, and Susp x 2

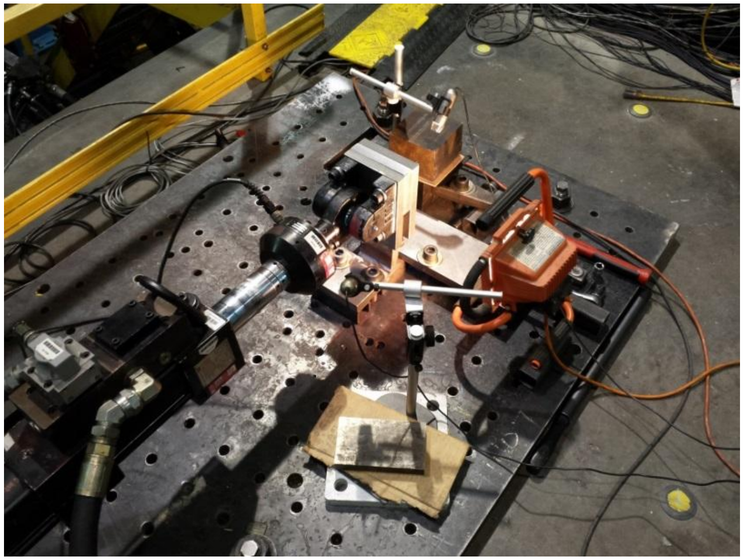
Test Log – 1st Round Welded Specimens, Constant, Block, & Variable Amplitude Loading

Specimen	Designation	Load (kN)	R Ratio P min / P max	Cycles	Notes (All tests run to failure)
-	Setup Test	24	0.1	36,895	Hand Weld
1	2-2	24	0.1	48,160	
11	-	24	0.1	62,047	
2	4-2	24	0.3	105,522	
3	4-3	24	LT/=0.5	262,628	Early in the test the minimium load went to 0 one time
13	-	24	0.5	349,002	
9	-	24	0.5	503,441	
15	4-4	20	0.5	592,250	Test Life Correction
8	-	17	0.5	4,901,846	No Crack
10	-	14	0.1	325,579	
-	-	14	0.1	375,813	
6	3-3	14	0.1	494,456	
7	3-1	14	0.3	922,658	
4	4-1	24	.1/.5	138,421	Total Cycles from Repeated Block (5k cycles @ R=0.1, 40k cycles @ R=0.5)
28	RBW_VA2	24	.1/.5	174,069	Total Cycles from Repeated Block (5k cycles @ R=0.1, 40k cycles @ R=0.5)
31	RBW_VA1_TBS	24	Variable	21	Repeats of Time History, Trans x 3, Brkt x 1, and Susp x 2
34	RBW_VA4_TBS	24	Variable	21	Repeats of Time History, Trans x 3, Brkt x 1, and Susp x 2

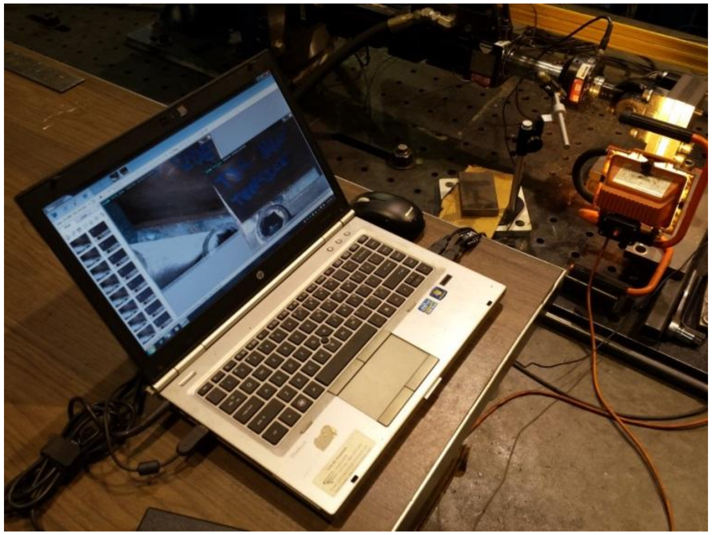
SAE FD&E T-Joint Test Set Up

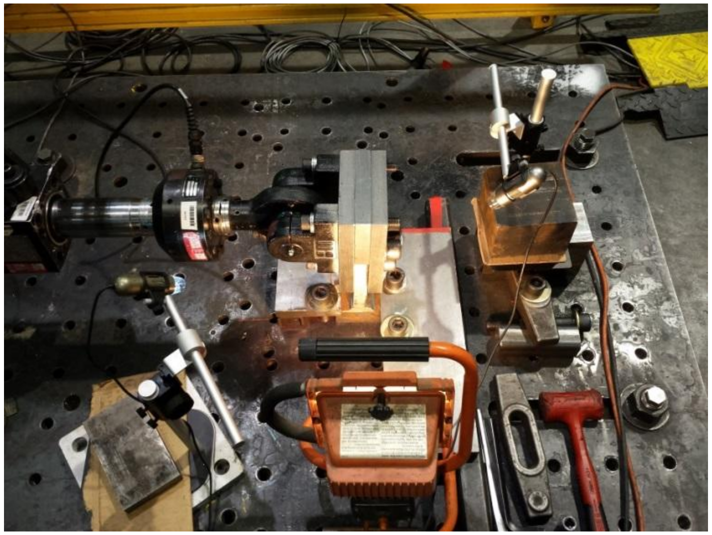
- MTS FlexTest IIm Controller
  - Load Control
  - Running tests at 5.1 Hz
- MTS 793 Series Software
  - Basic Testware (constant amplitude)
  - MultiPurpose Testware (block loading)
  - RPC Pro (variable amplitude loading TBS)
- MTS 244 Series Hydraulic Actuator
  - 11 Kip (50 kN) x 6” (152 mm) stroke
  - 252.25 Series dual stage servo valve
  - MTS Load cell and LVDT
- SOMAT eDAQ Lite
  - Record time history file
  - Collecting Load & Displacement
  - Collect strain on certain specimens
- Dino-Lite USB Cameras / Laptop
  - Capture time-lapse video at weld toe

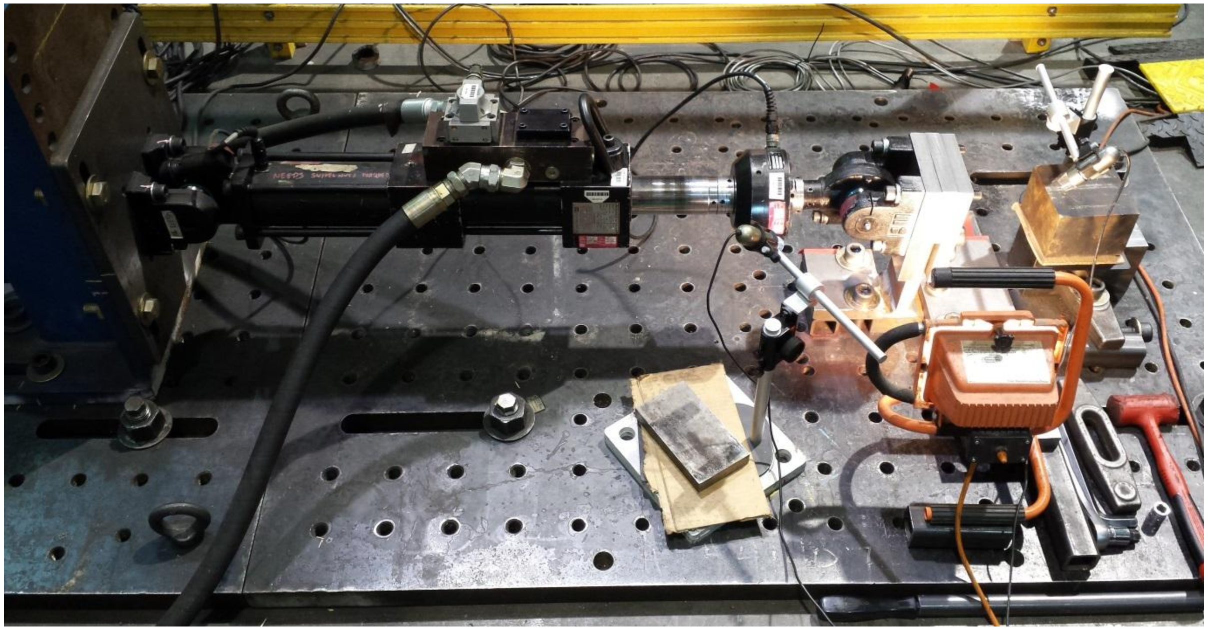




SAE FD&E T-Joint Test Set Up

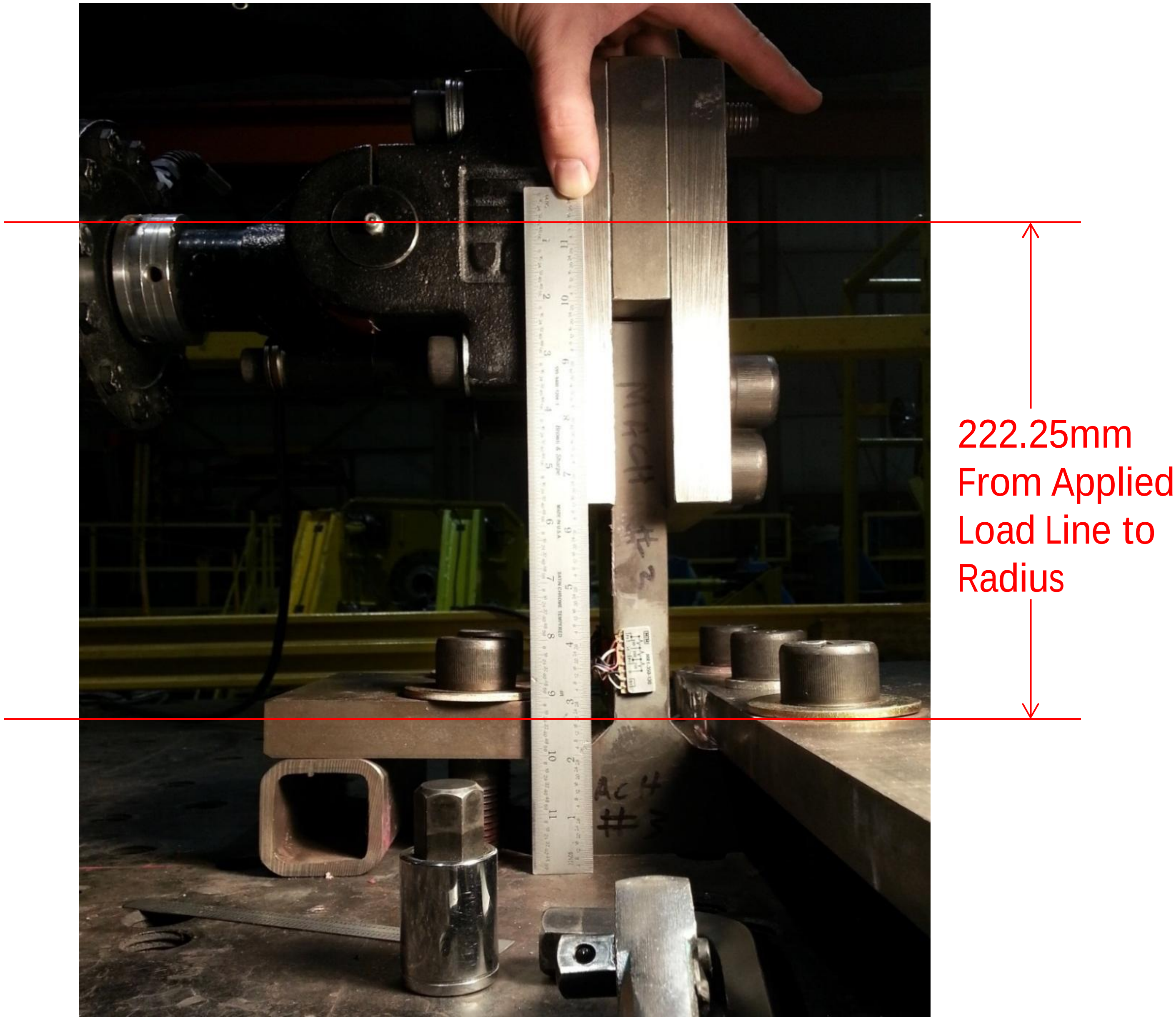






Total Fatigue Life: Crack Initiation and Crack Propagation…Test Results

Specimen in Test Fixture/ for FEM Boundary Conditions

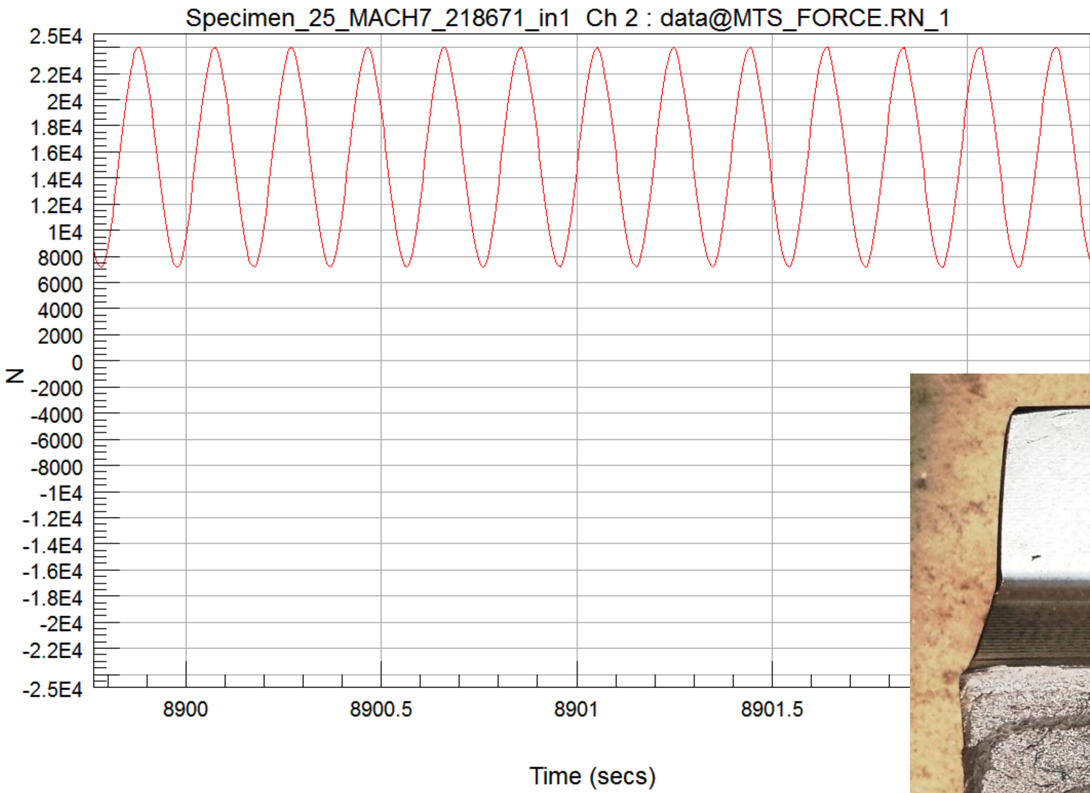


Machined T-Joint Specimens

- 24 kN, R= 0.3
- 24 kN, R= 0.1
- 18 kN, R= 0.1
- 10.8 kN, R= -1
- 24 kN, Variable Amplitude, Block Loading
- 24 kN (Max/Min), Variable Amplitude,
  Time History File (Tx3, Bx1, Sx2)

Total Fatigue Life: Crack Initiation and Crack Propagation…Test Results

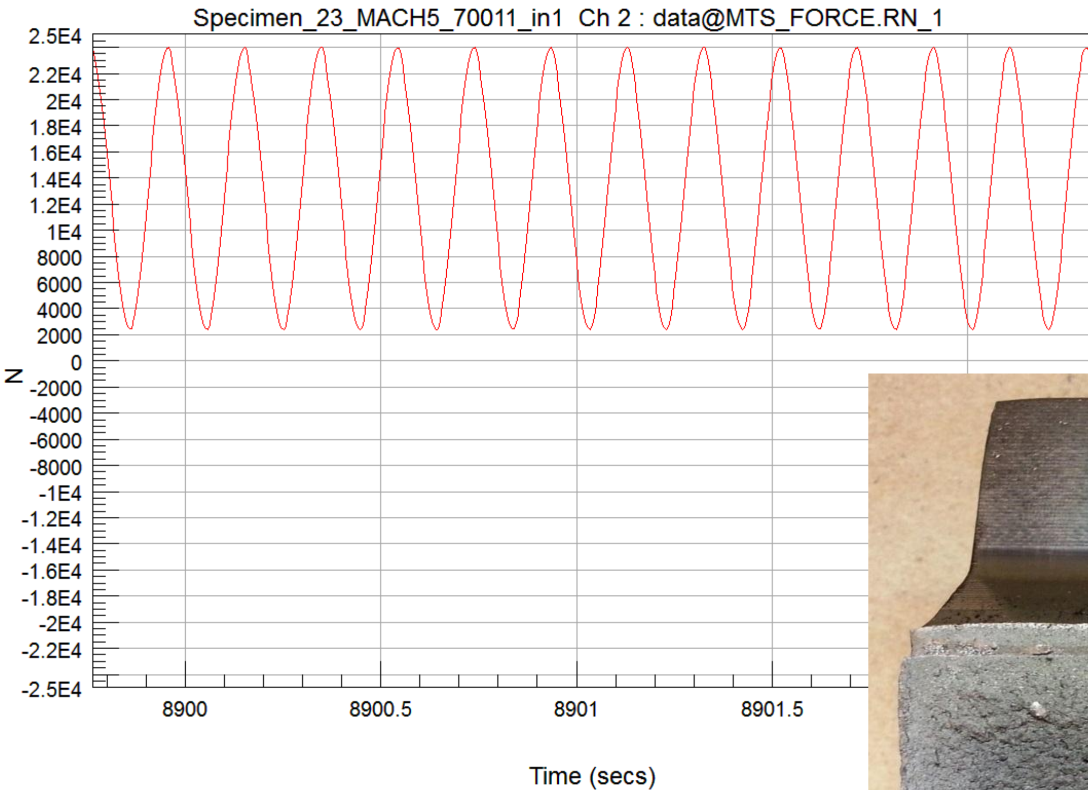
24 kN, R= 0.3



Highest Mean Load -
Crack Has Not Reached Free End

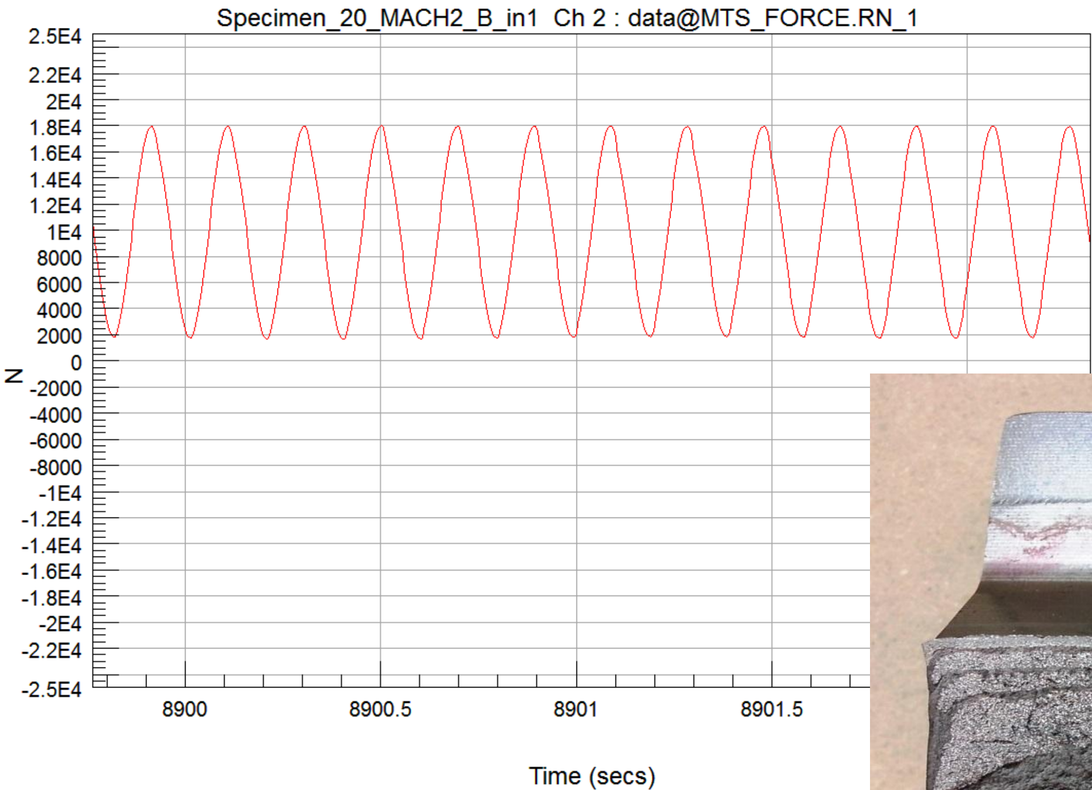
Total Fatigue Life: Crack Initiation and Crack Propagation…Test Results

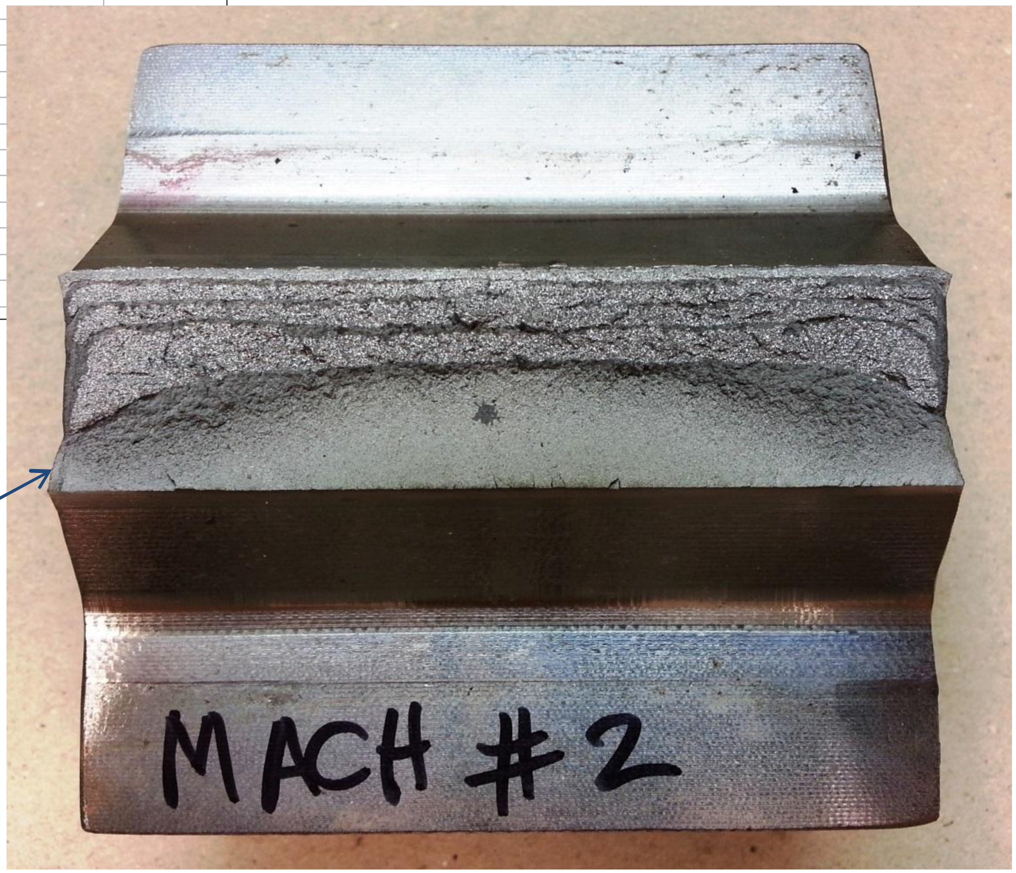
24 kN, R= 0.1



Total Fatigue Life: Crack Initiation and Crack Propagation…Test Results

18 kN, R= 0.1

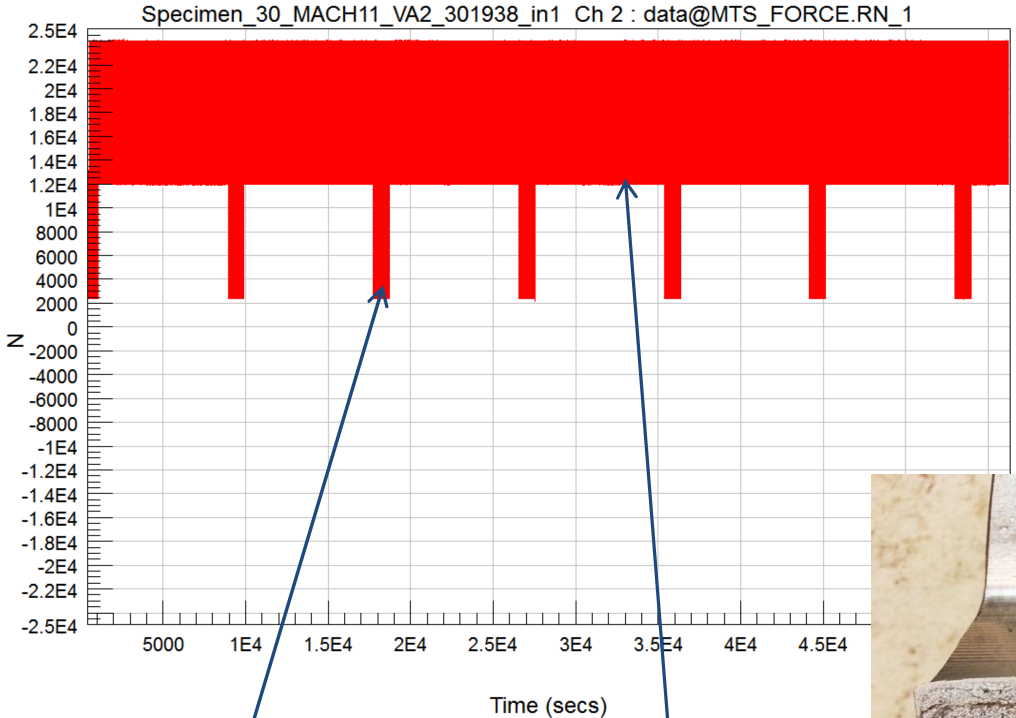




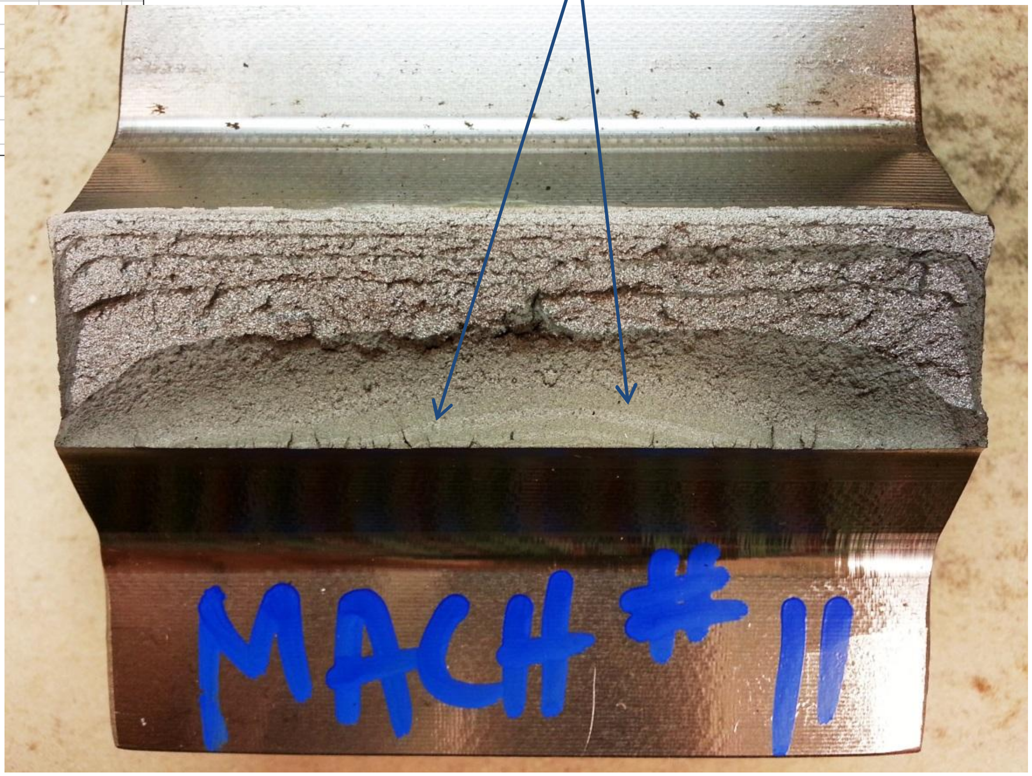
Lowest Mean Load -
Crack Has Reached Free End

Total Fatigue Life: Crack Initiation and Crack Propagation…Test Results

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



Marker Bands
(Blocks of Striations at a Load Level)

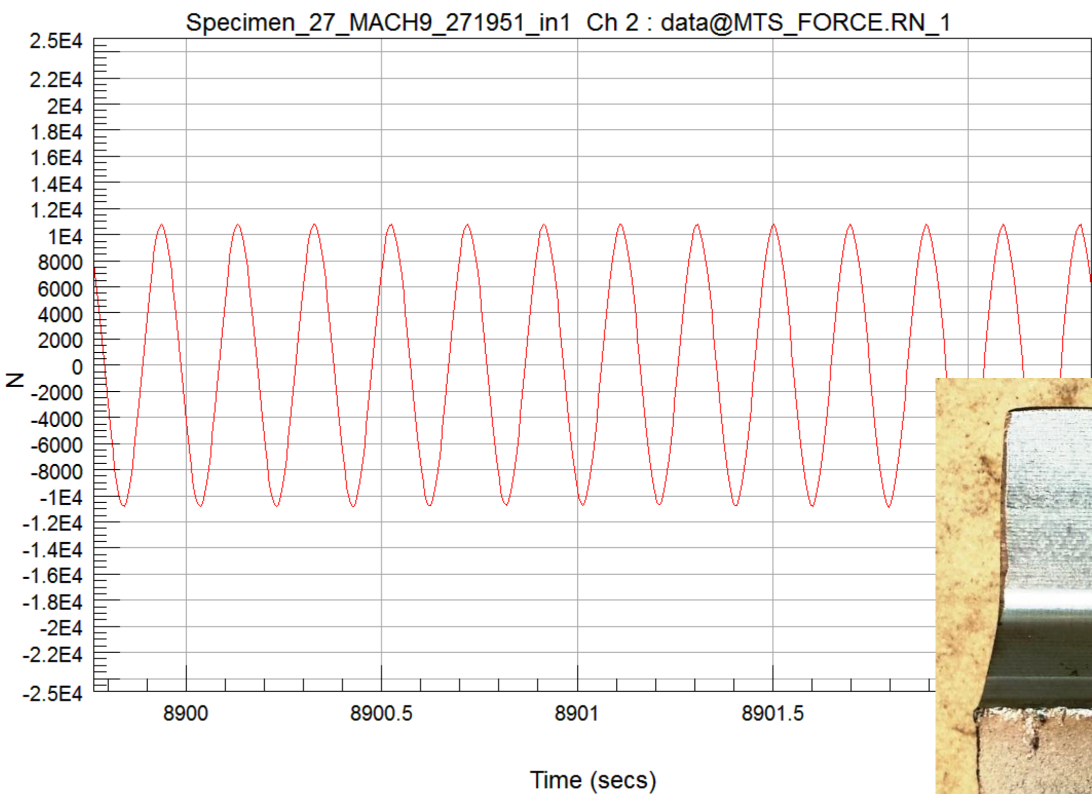


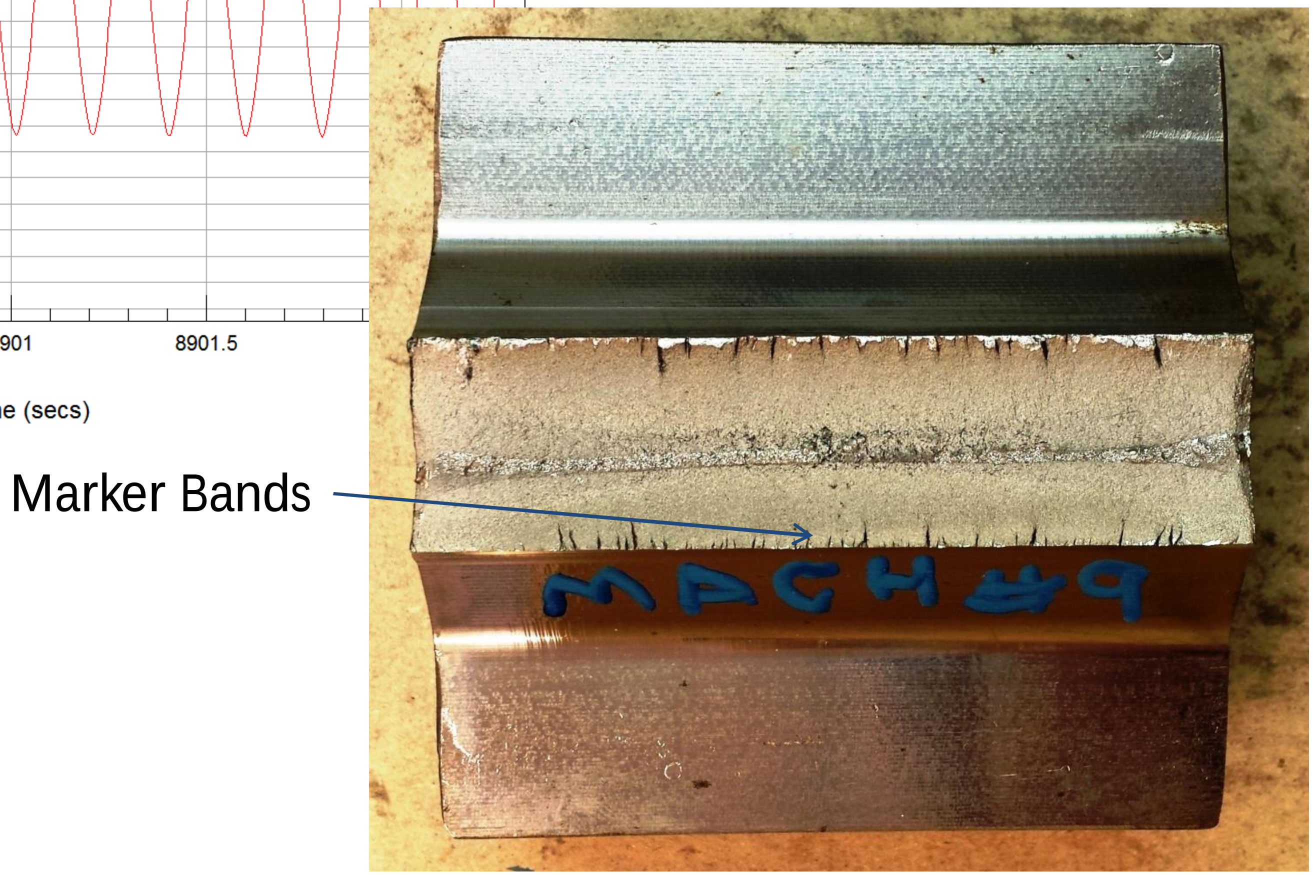
5,000 Cycles
24 kN, R= 0.1

40,000 Cycles
24 kN, R= 0.5

Total Fatigue Life: Crack Initiation and Crack Propagation…Test Results

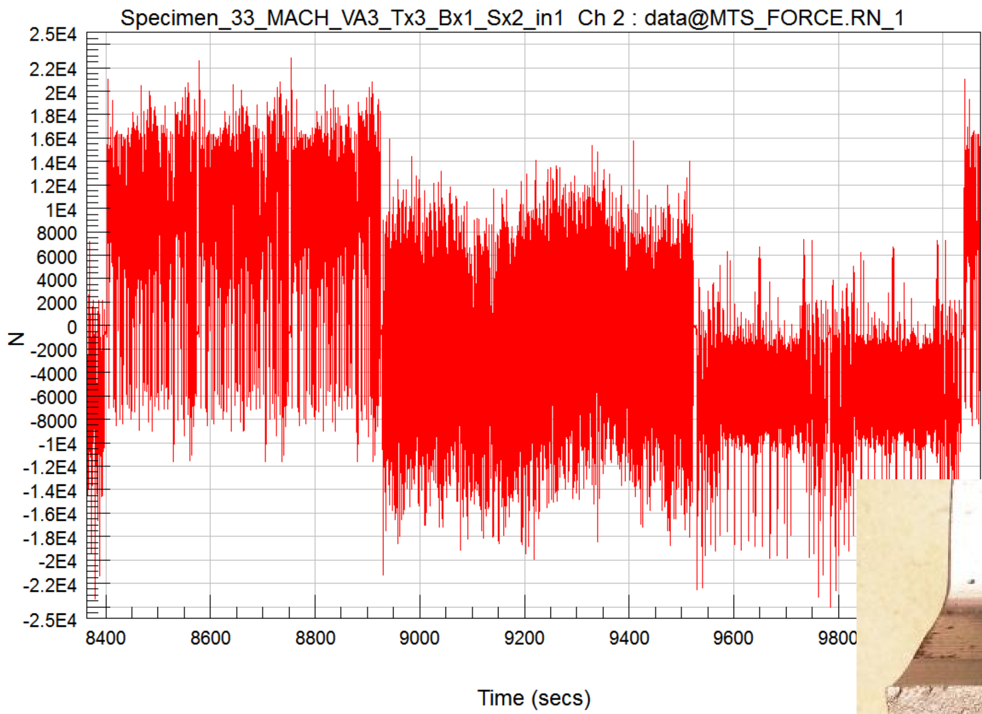
10.8 kN, R= -1





Total Fatigue Life: Crack Initiation and Crack Propagation…Test Results

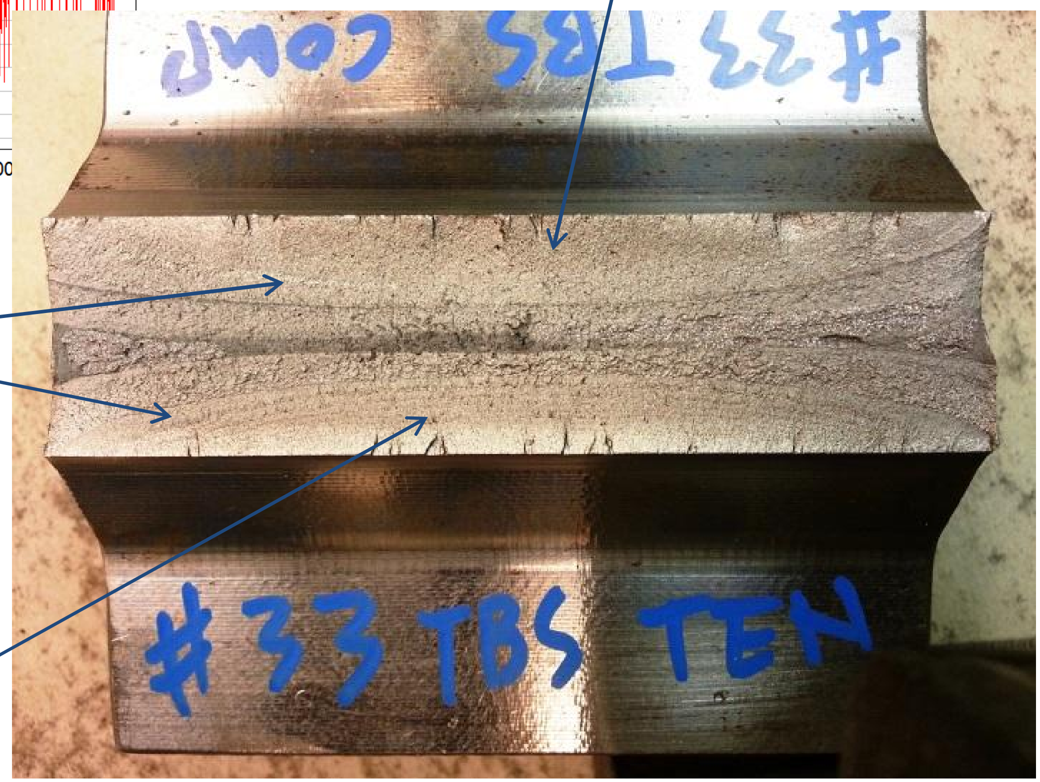
24 kN Max / 24 kN Min, VA, Time History Profile (Trans x3, Brkt x1, Susp x2)



Side of First Cycle In Compression

Marker Bands

Side of First Cycle In Tension



RPC Iterations

The variable amplitude load histories were created through an iteration process using an MTS Software package called RPC Pro.

When iterating a test, the goal is to match the signal response to the signal command

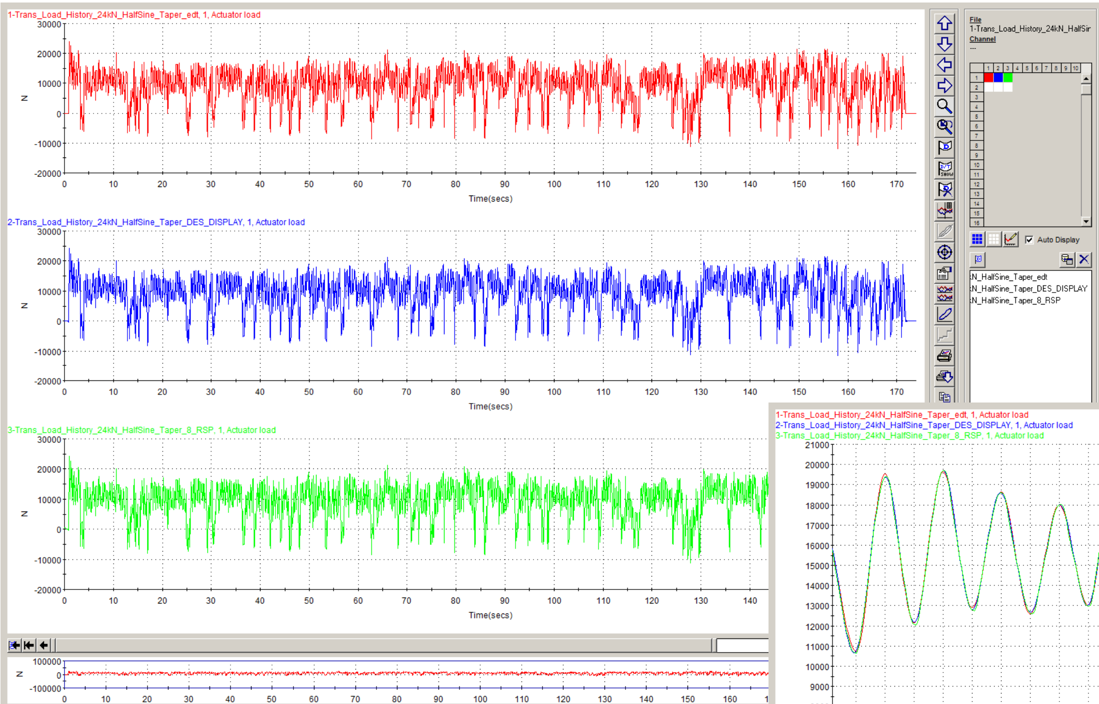
For this testing SAE used the transmission, bracket, and suspension load histories that were used in previous SAE fatigue experiments (SAE AE-6, 1977)

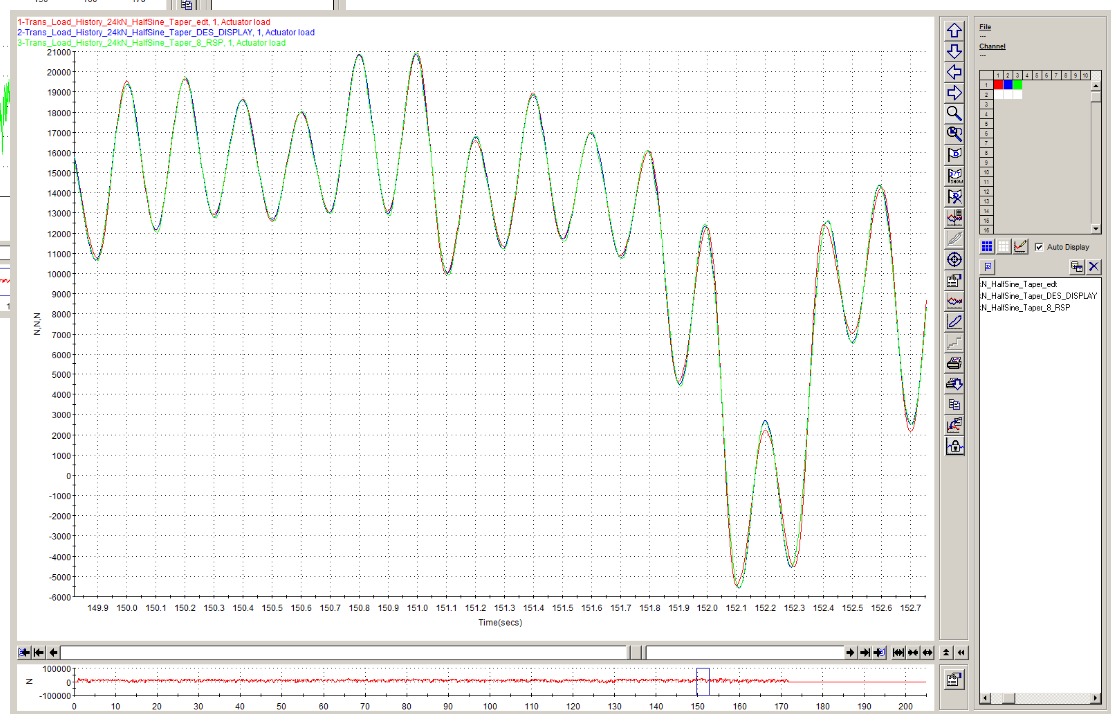
Load histories were developed for the total life project individually then concatenated together for a complete variable amplitude time history

Simplified Process –
Create edt (real or edited time history)
Generate desired display (filtered edt)
Iterate the time history until the feedback signal (response) matches the command signal (desired display)

We are able to very accurately duplicate the command signal due to the iterative capability of RPC Pro

RPC Iterations – Transmission Time History



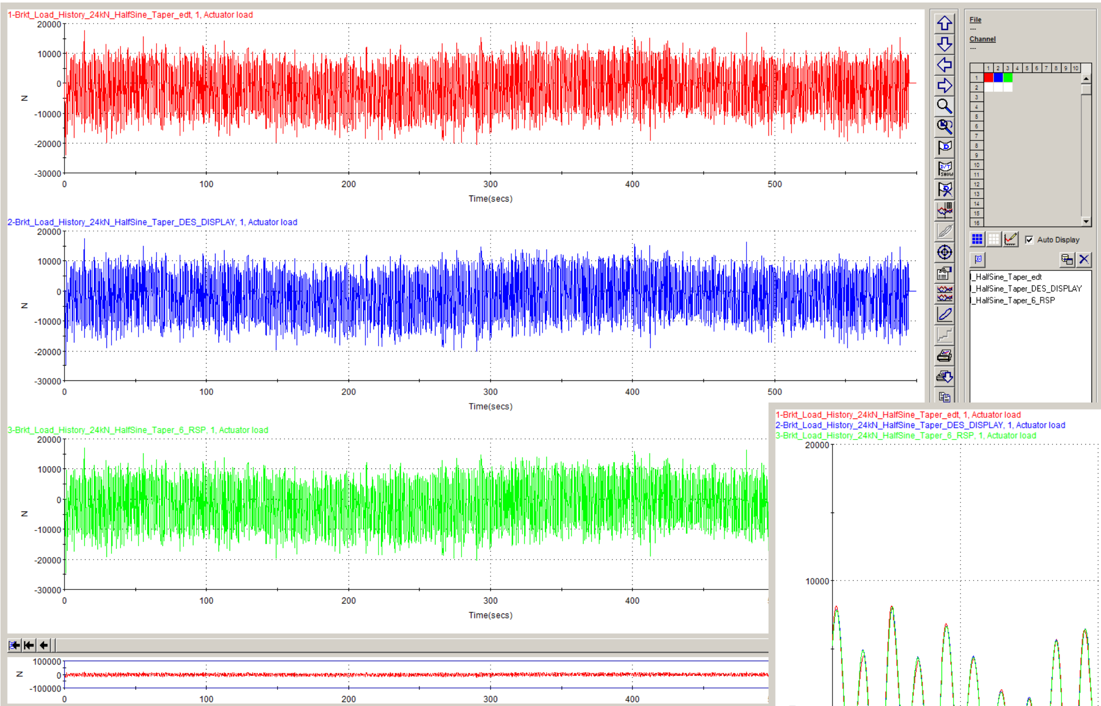


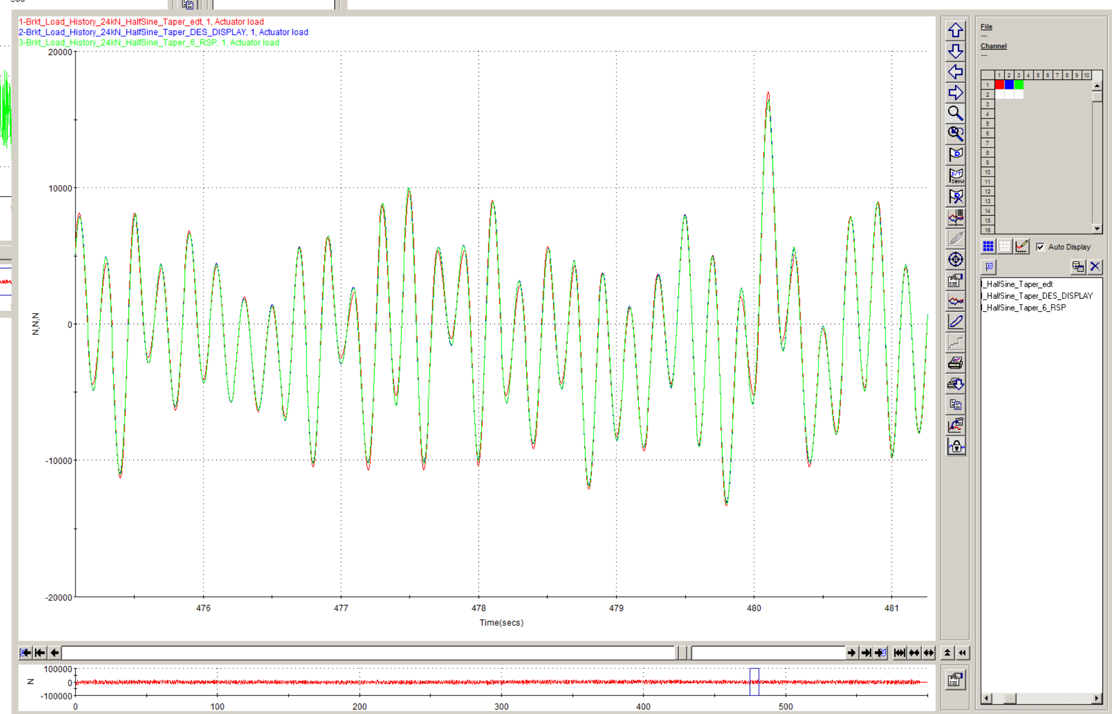
Red – edt
Blue – des display
Green – rsp

Transmission load history mean is primarily tensile

8 Iterations

RPC Iterations – Bracket Time History



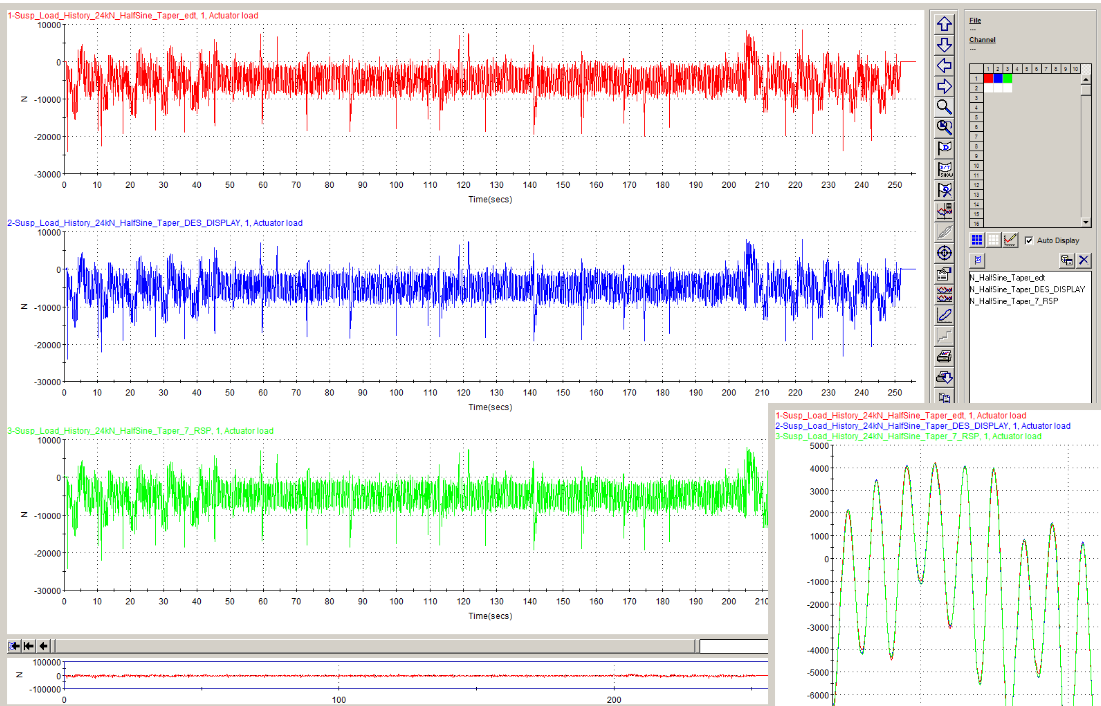


Red – edt
Blue – des display
Green – rsp

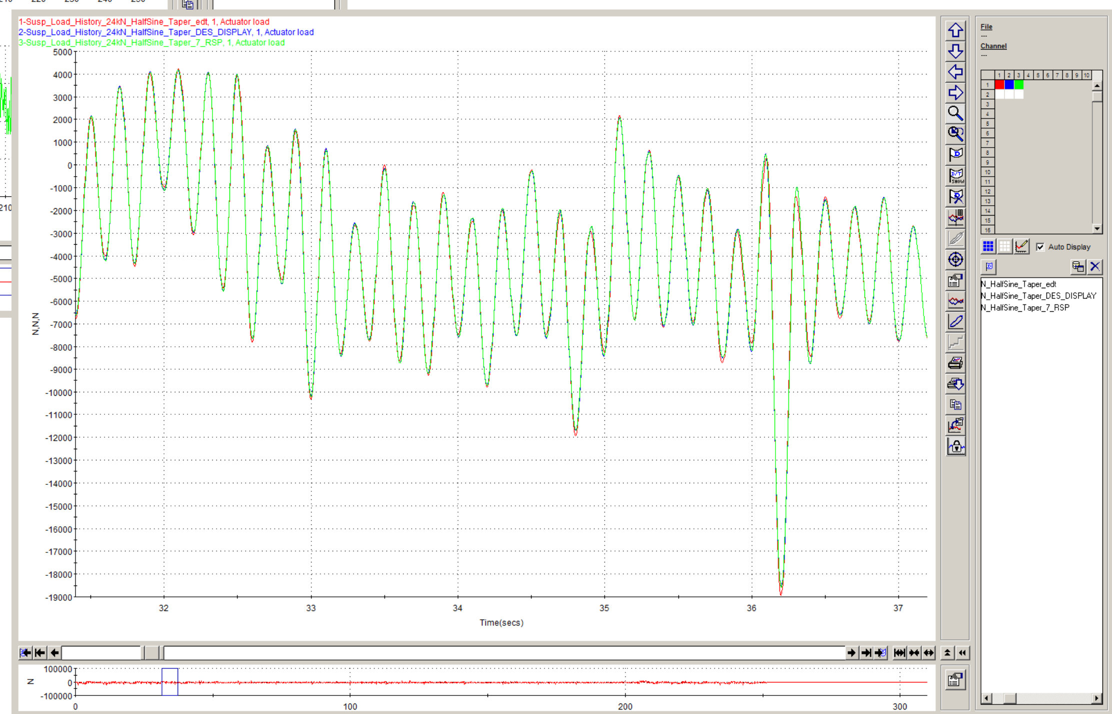
Bracket load history
mean is primarily around zero

6 Iterations

RPC Iterations – Suspension Time History



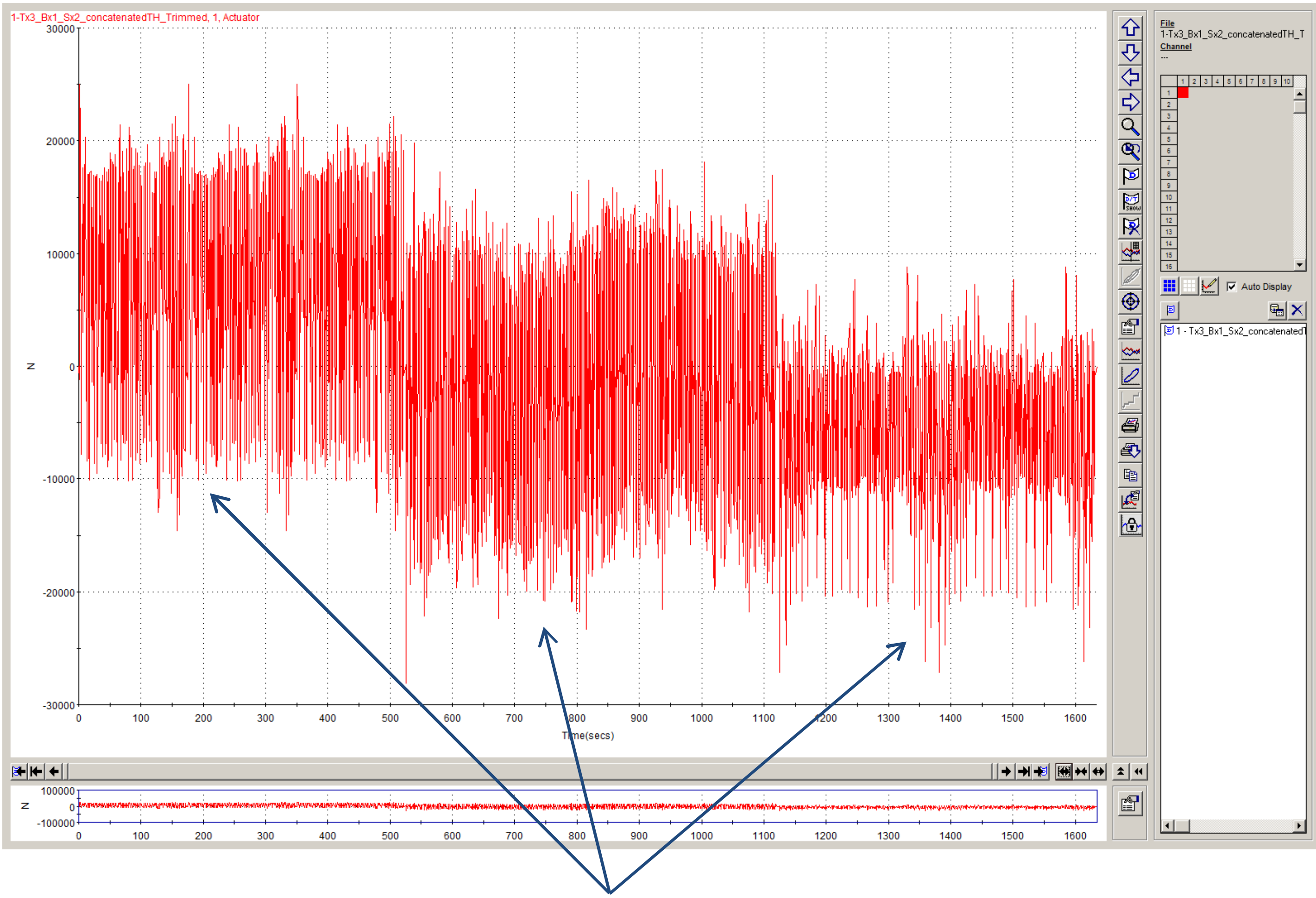
Red – edt
Blue – des display
Green – rsp



Suspension load history mean is primarily compressive

7 Iterations

RPC Iterations – Final Drive



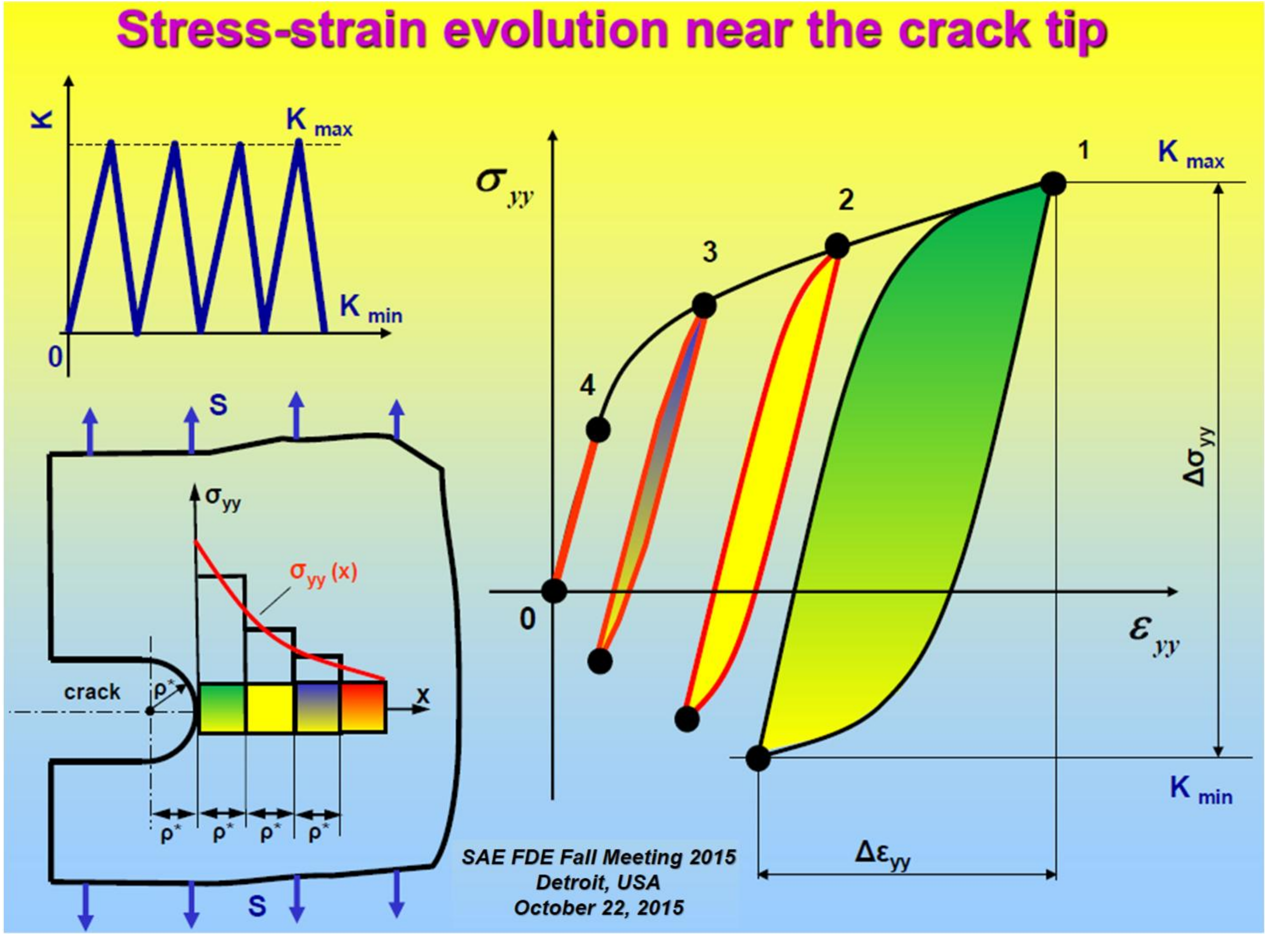
Complete Drive File –
3 Repeats of Transmission, 1 Repeat of Bracket, 2 Repeats of Suspension

Total Fatigue Life: Crack Initiation and Crack Propagation….Whole Life

Method: Whole Life Machined and Welded Fatigue Life Predictions

Reference:

[1] Mikheevskiy, S., 2009, “Elastic-Plastic Fatigue Crack Growth Analysis Under Variable Amplitude Loading Spectra,” PhD thesis, University of Waterloo.



Total Fatigue Life: Crack Initiation and Crack Propagation….Whole Life

29 A36 T-Joint Test Results to Date

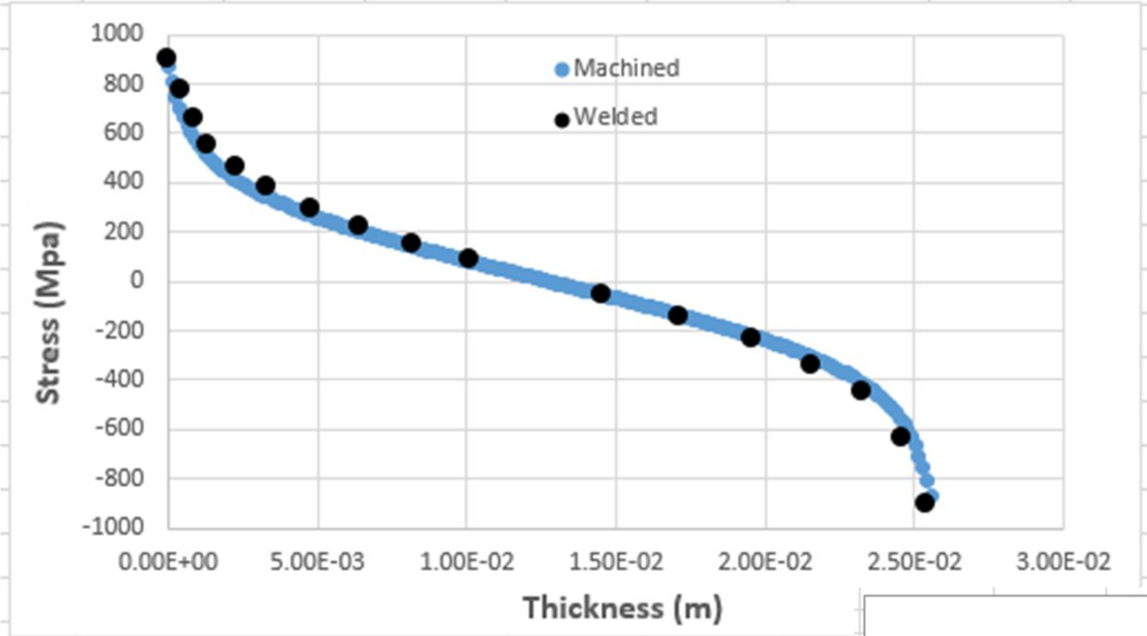
Machined Specimens (13)			
Max Load (kN)	Max Stress MPa	R Ratio Dimensionless	Experimental Test Life Cycles
24***	870.44	0.5	2,471,943
24****	870.44	0.1	58,481
24	870.44	0.1	70,011
24	870.44	0.3	218,671
24	870.44	0.3	200,464
18*****	652.83	0.1	424,431
18	652.83	0.1	411,745
14***	507.67	0.1	3,495,011
10.8	391.70	-1	214,765
10.8	391.70	-1	271,951
24	870.44	*Block Ld: 0.1/0.5	326,135
24	870.44	*Block Ld: 0.1/0.5	301,938
24	870.44	**Var Amplitude	224,672
24	870.44	**Var Amplitude	232,696

Note: *5k 24kN R=0.1 Cycles followed by 40k 24kN R=0.5 Cycles
**3xSAE Transmission+1xBracket+2Suspension PV File
***Run out
****Tested after R=0.5 run out
*****Tested after R=0.1 run out

Welded Specimens (17)			
Max Load (kN)	Max Stress MPa	R Ratio Dimensionless	Experimental Test Cycles
24	902.62	0.1	36,895
24	902.62	0.1	48,160
24	902.62	0.1	62,047
14	526.53	0.1	325,579
14	526.53	0.1	375,813
14	526.53	0.1	494,456
24	902.62	0.3	105,522
14	526.53	0.3	922,658
24	902.62	0.5	262,628
24	902.62	0.5	503,441
24	902.62	0.5	349,002
20	752.18	0.5	592,250
17***	639.36	0.5	4,901,846
24	902.62	*Block Ld: 0.1/0.5	138,421
24	902.62	*Block Ld: 0.1/0.5	174,069
24	902.62	**Var Amplitude	168,504
24	902.62	**Var Amplitude	168,504

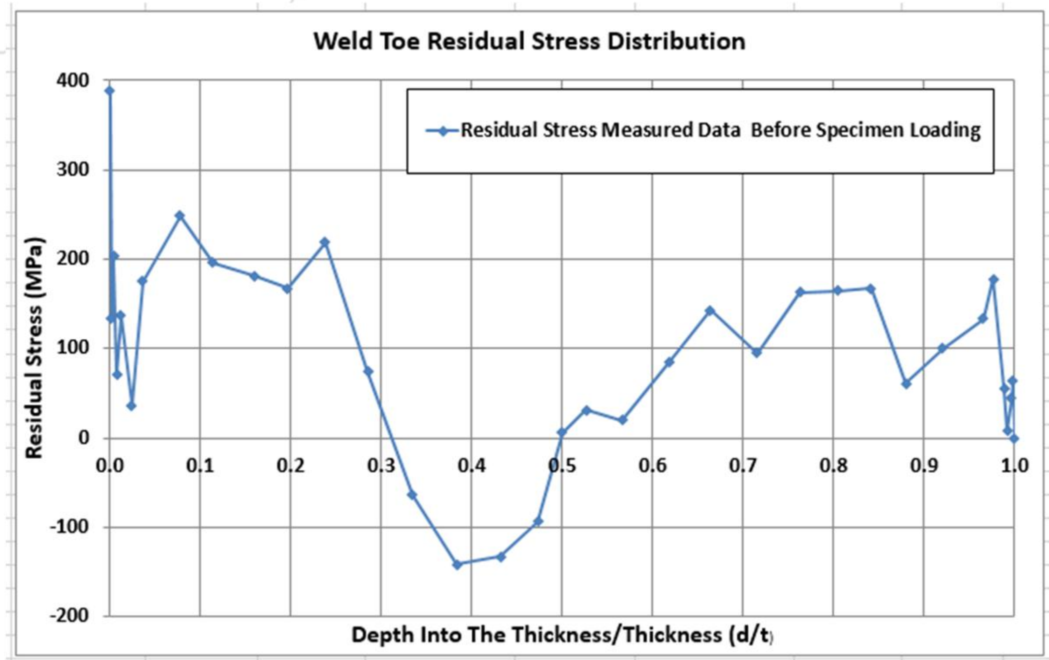
Total Fatigue Life: Crack Initiation and Crack Propagation Analysis … Whole Life

Comparison - Welded to Machined FEM Stress Distributions

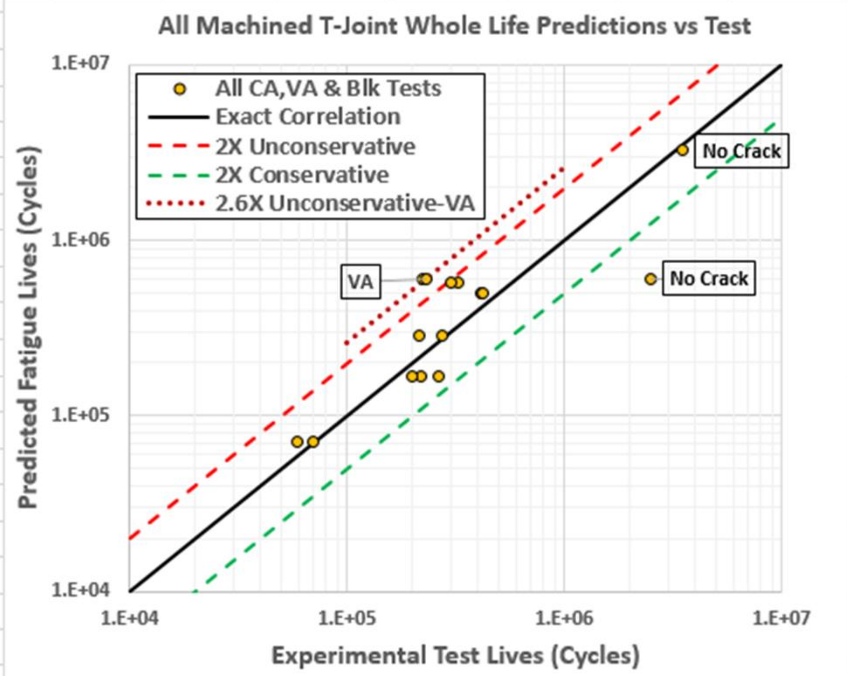


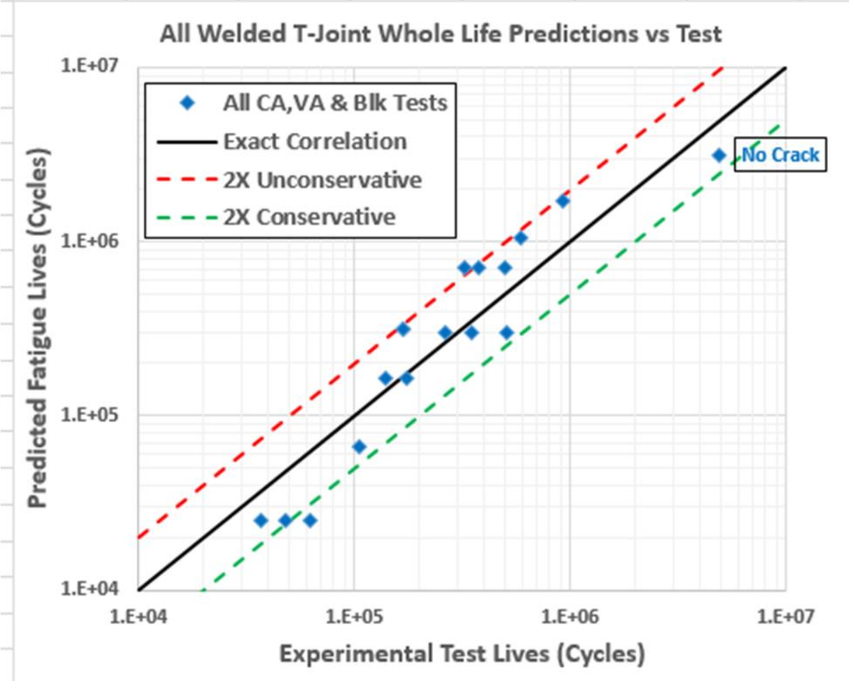
The welded analysis was exactly the same as the machined analysis except the FEM stress distribution input was changed (slightly) from the machined distribution to the welded distribution as shown in the figure on the left.....

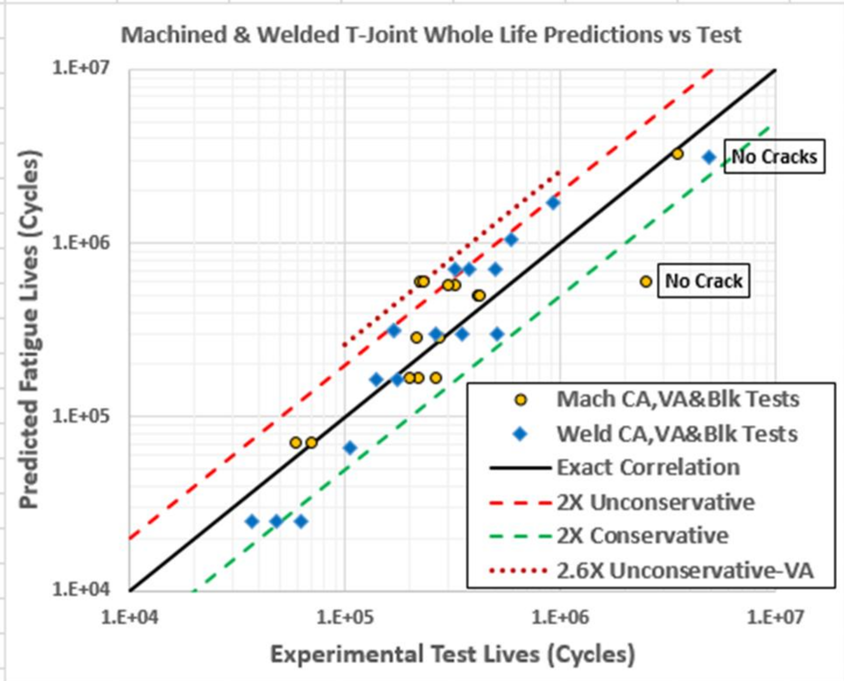
And the welding residual stress distribution (shown in the figure on the right) was included in the welded analysis. No residual stress distribution was input in the machined analysis.



Total Fatigue Life: Crack Initiation and Crack Propagation Analysis … Whole Life



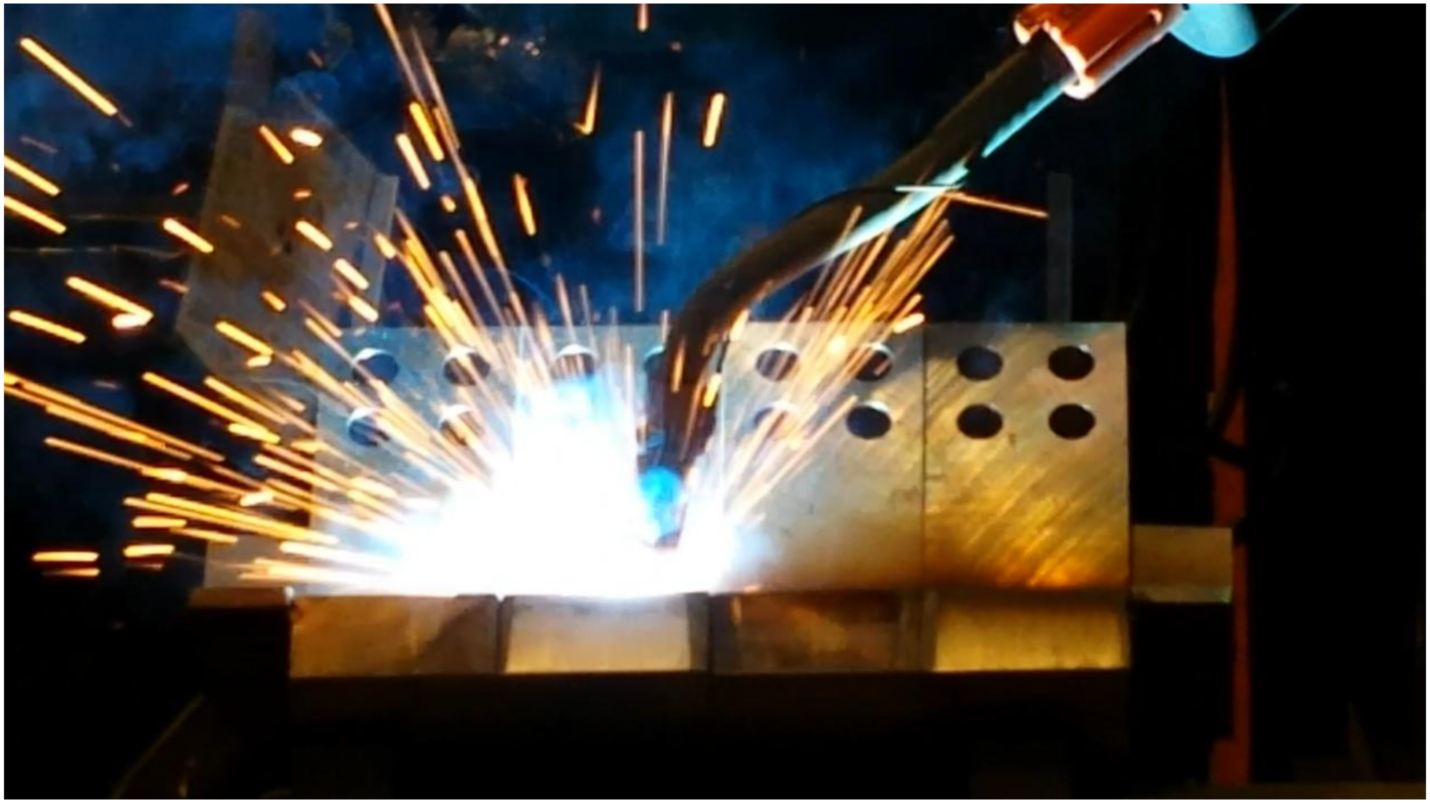




Whole Life Fatigue Life Predictions to *"Failure"*

1)The fatigue life predictions of the welded samples appear to be consistent with the fatigue life predictions of the machined samples.

2)All the predicted fatigue lives fall within scatter bands of approximately +/- 2 times the test lives to failure – except the machined variable amplitude predicted fatigue lives. Those two test predictions were approximately +2.6 times the test lives to failure.



2^{nd} Round Welded Specimens

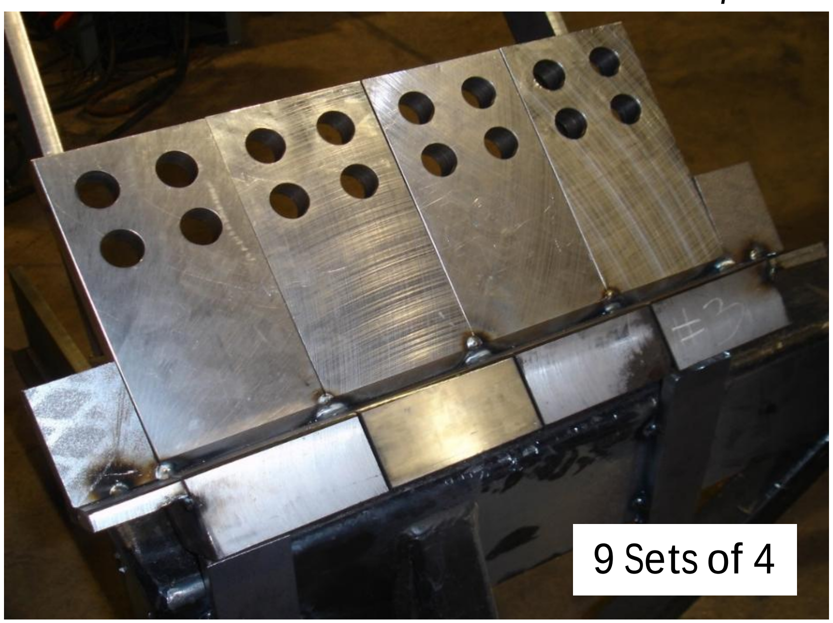
Total Fatigue Life: Crack Initiation and Crack Propagation Analysis … Whole Life

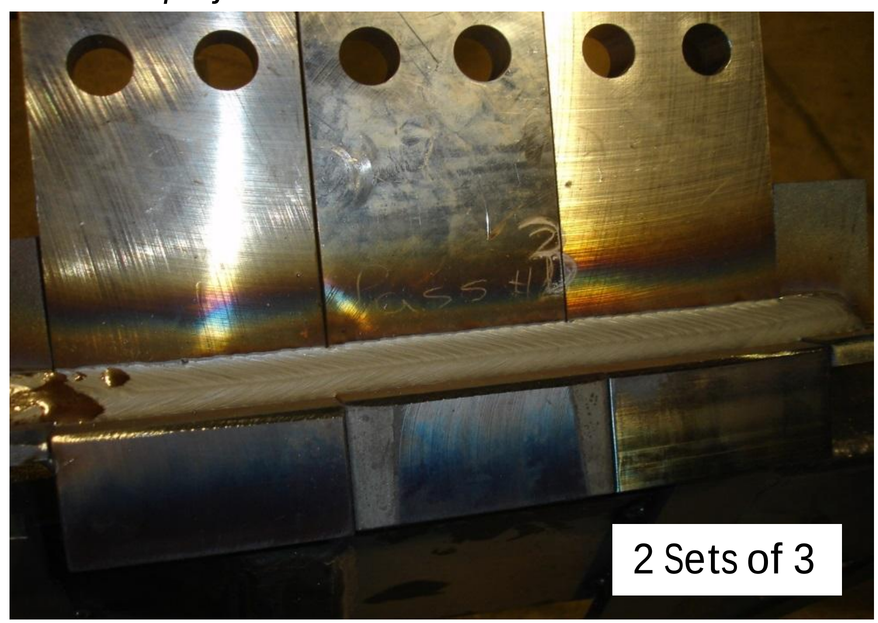
Welding Process

Weld	Side	Starting End	Voltage	Current	Wire Speed	Travel Speed	Work Angle	Cooling Time*
1	1	A	38.5 V	235 A	7 m/min	40 cm/min	45	NA
2	2	B	38.5 V	235 A	7 m/min	40 cm/min	45	45 s
3	2	B	39.0 V	300 A	8 m/min	35 cm/min	45	3 s
4	2	B	39.5 V	225 A	8.5 m/min	60 cm/min	45	3 s
5	1	A	39.0 V	300 A	8 m/min	35 cm/min	45	1 m 30 s
6	1	A	39.5 V	225 A	8.5 m/min	60 cm/min	45	2 m 30 s

Parameter/Characteristic	Value
Welding Process	(GMAW)
Wire Type	(Solid)
Wire Diameter	0.062 inches
Shielding Gas	90% CO2/ 10% Ar
Base Material	A36
Filler Metal	ER70S-6
Welding Position	45 deg for all weld passes

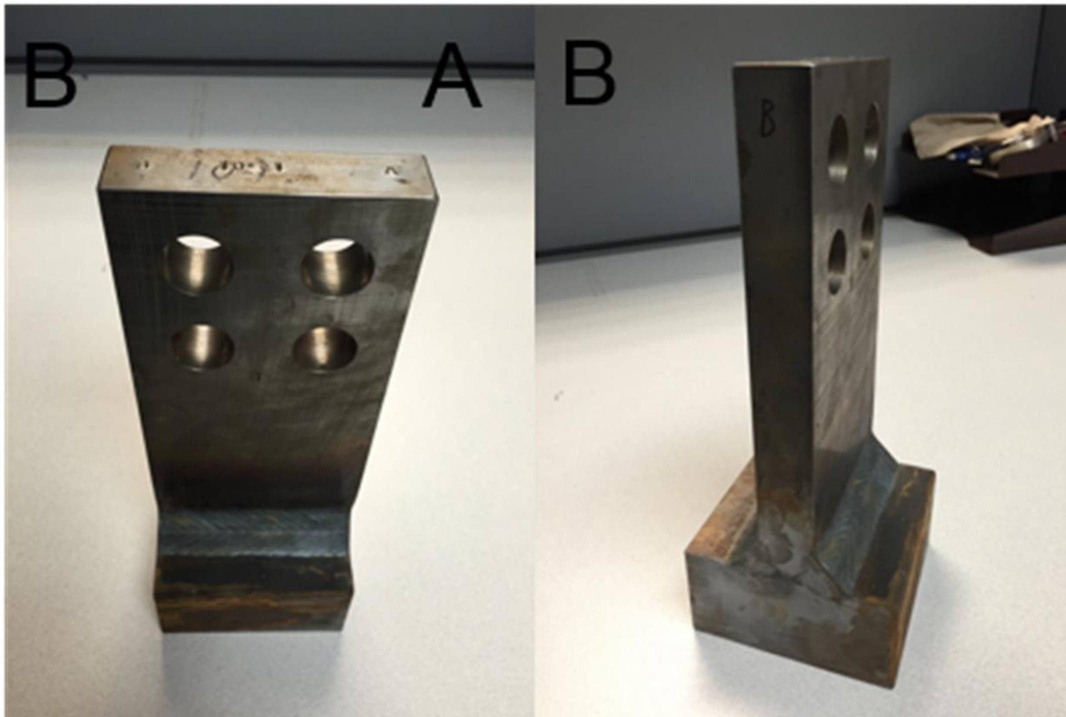
** Tabular data was provided by SAE FD&E project members.*

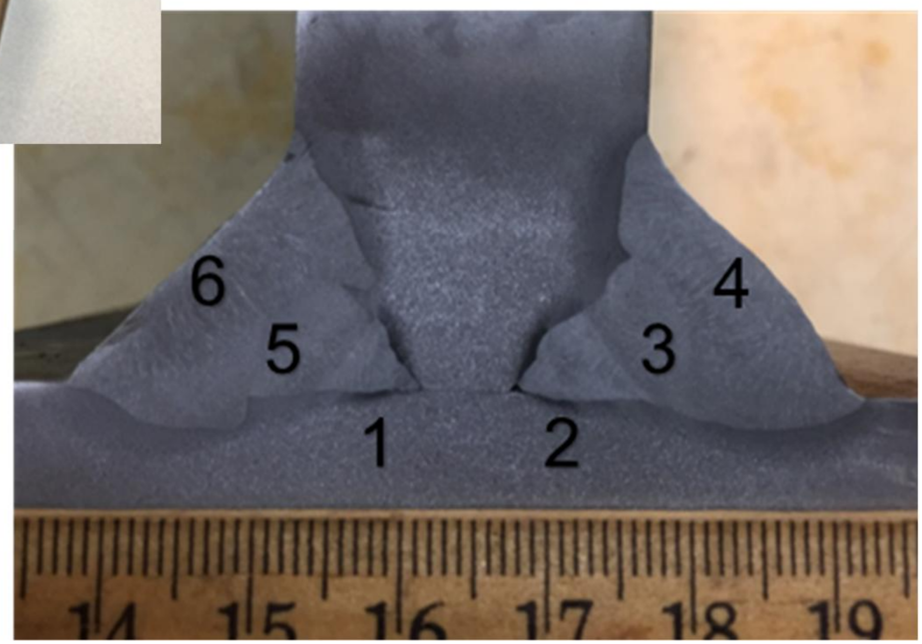




Total Fatigue Life: Crack Initiation and Crack Propagation Analysis … Whole Life

Welding Sequence

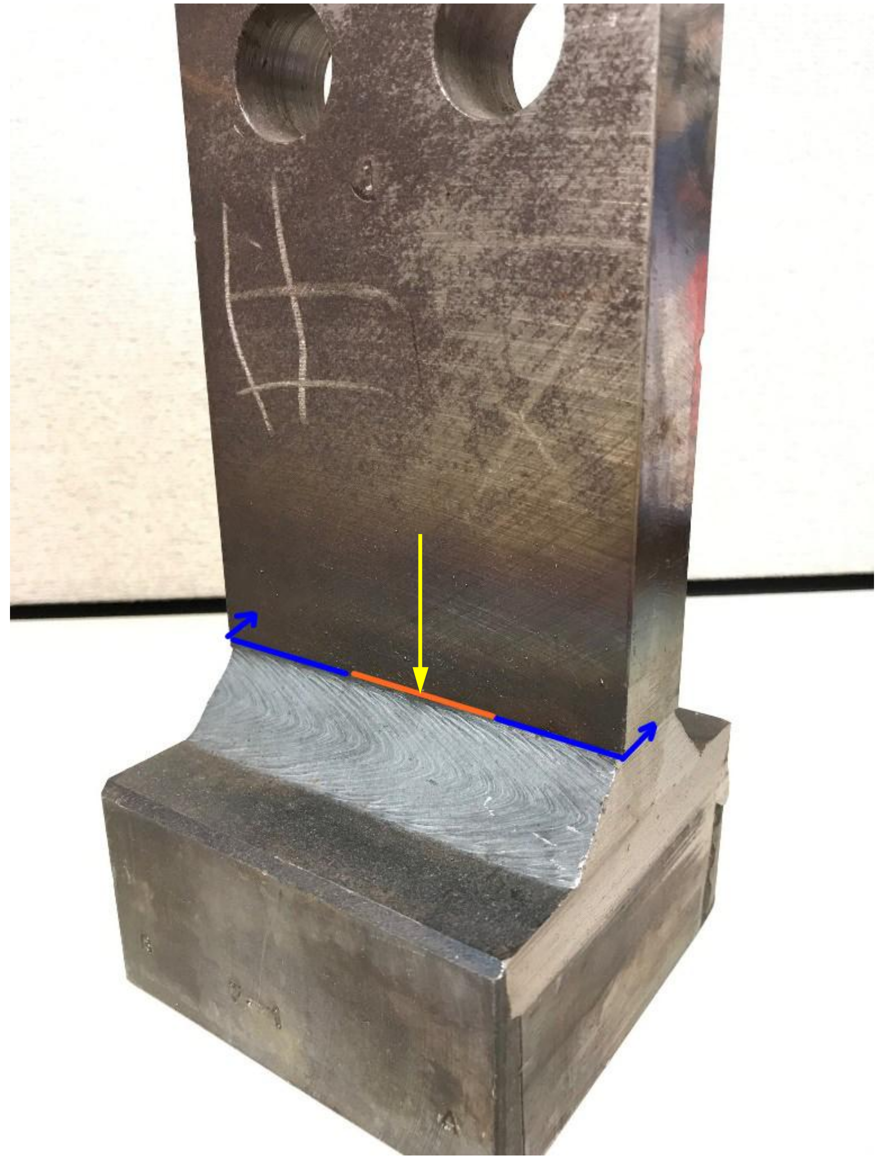




Total Fatigue Life: Crack Initiation and Crack Propagation Analysis … Whole Life

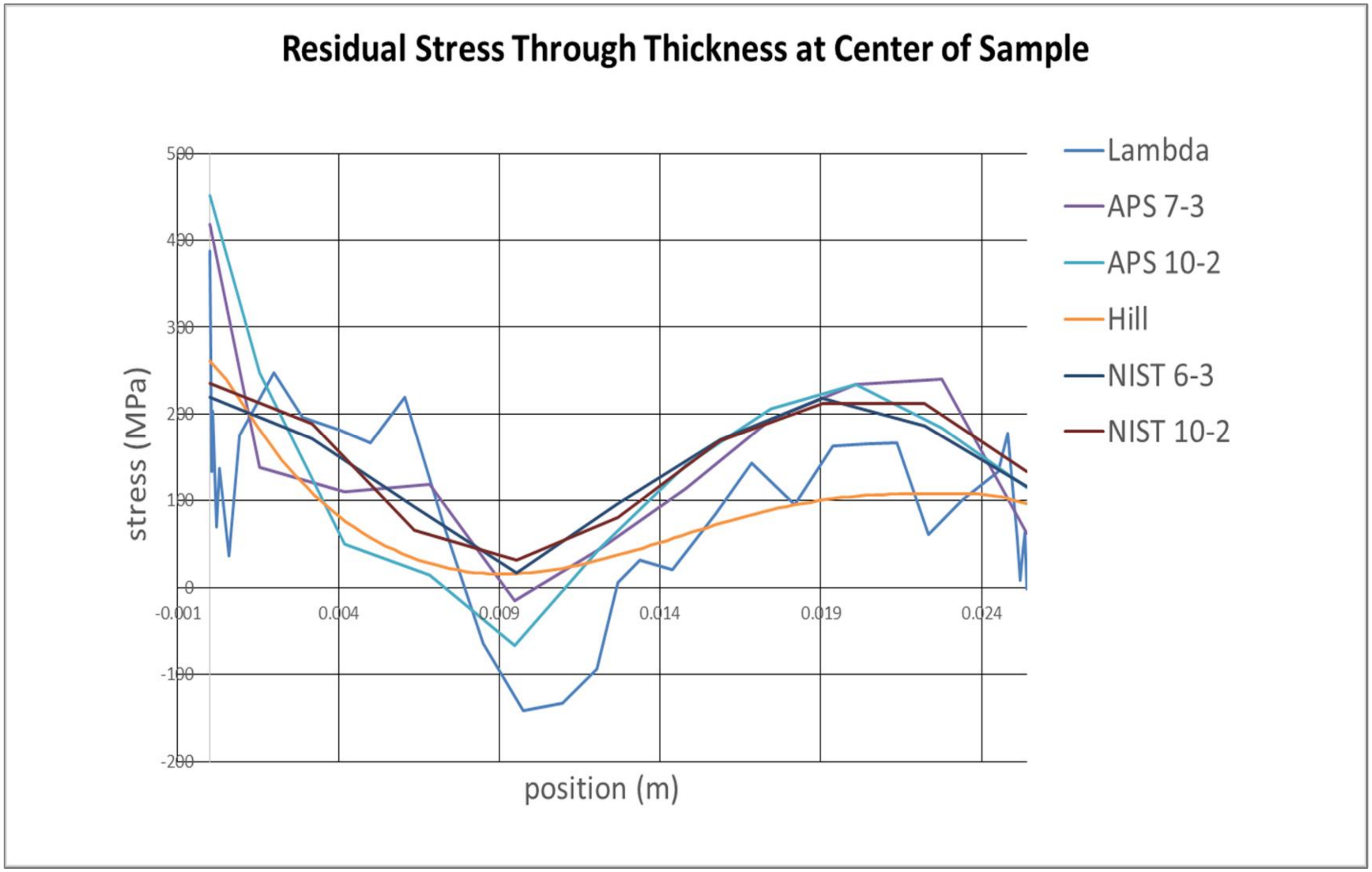
Residual Stress Measurements

- Residual stress measurements taken at the center, through the part
- Position 0 is the front surface of vertical plate
- Position 0.0254m is the back surface of vertical plate



Total Fatigue Life: Crack Initiation and Crack Propagation Analysis … Whole Life

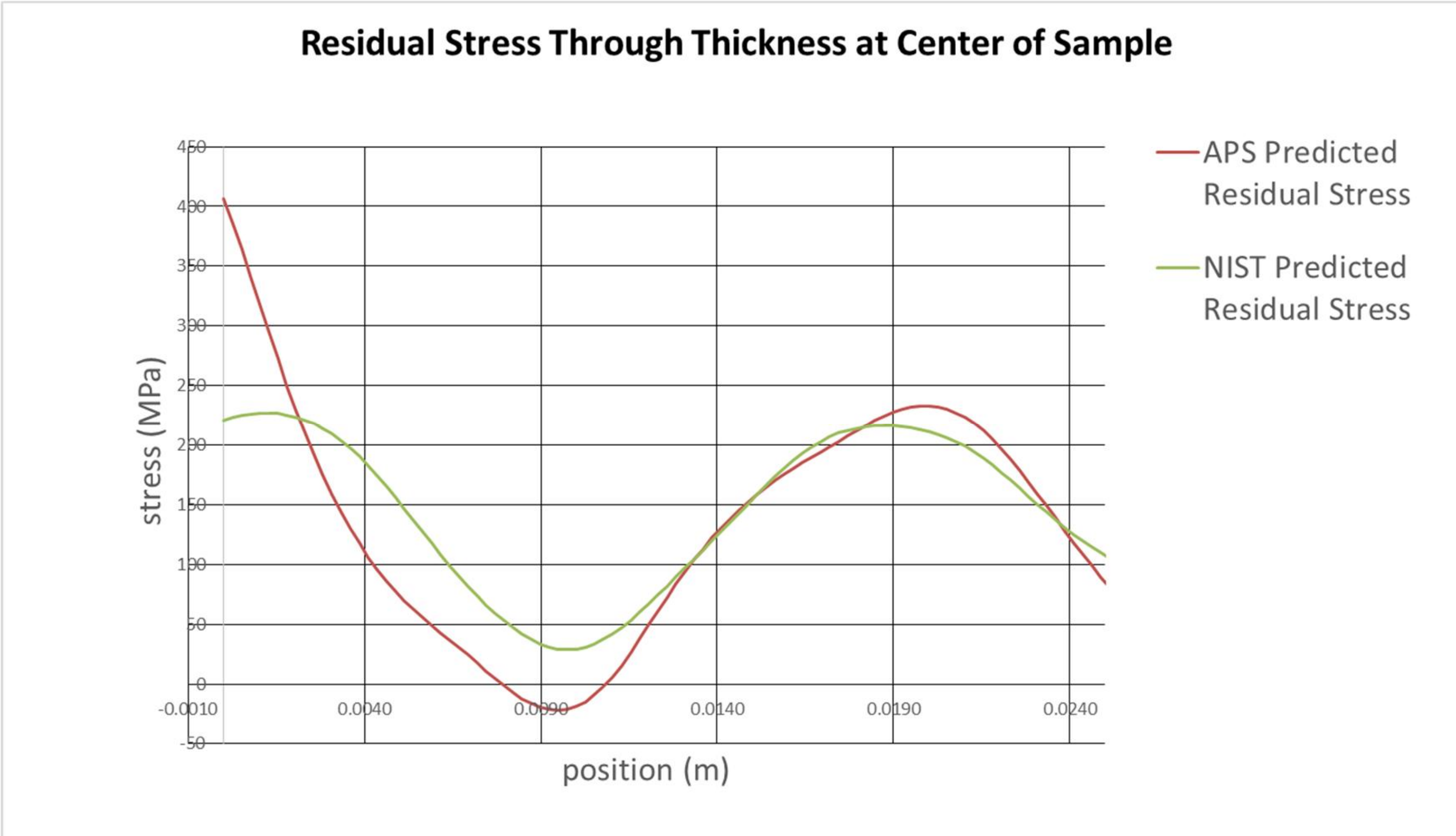
Residual Stress Measurements



- Large variation in magnitudes of stress at position 0
- 452MPa to 219MPa
- Lambda RSD From Round 1

Total Fatigue Life: Crack Initiation and Crack Propagation Analysis … Whole Life

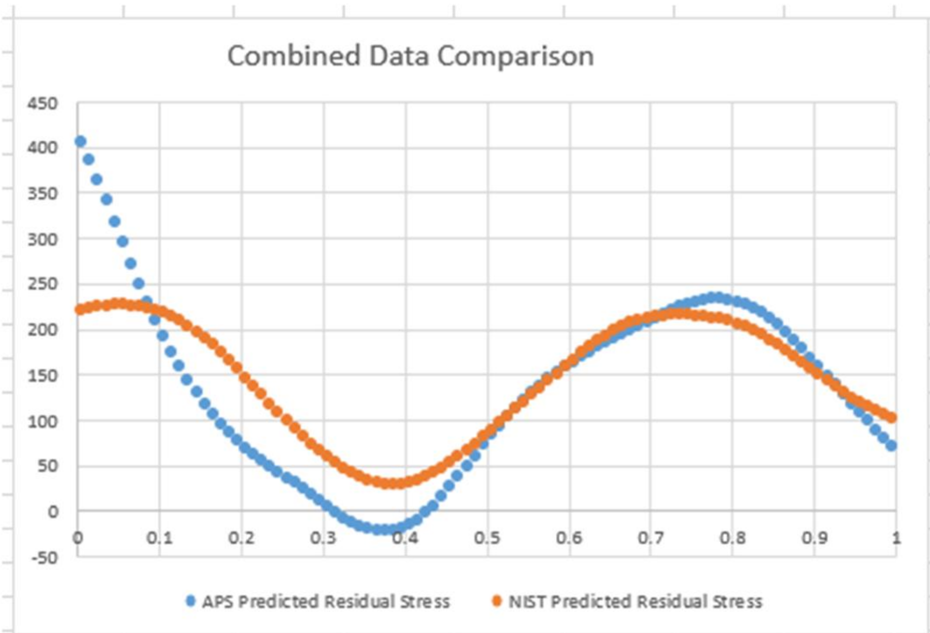
Residual Stress Measurements

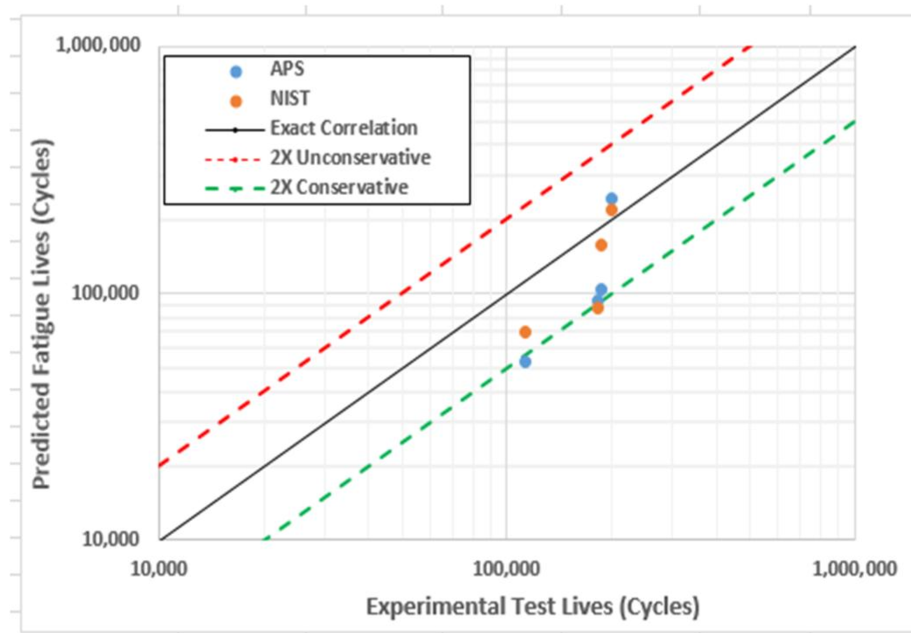


- Data provided by Mark Andrews – SmartUQ
- Generated through uncertainty analysis of the APS and NIST sample data

Total Fatigue Life: Crack Initiation and Crack Propagation Analysis… Whole Life
Evaluate Residual Stress Distributions Obtained by Two Different Methods

Specimen	Designation	Load (kN)	R Ratio (σ_{min} / σ_{max})	Cycles	Notes	Stress Mpa	APS		NIST	
36	RBW2_2.2	18	0.1	185,863	Side 2 in tension, **Higher tensile residual stress**	676.965	**104,616**	-0.44	**156,086**	-0.16
37	RBW2_2.3	18	0.1	201,168	Side 1 in tension, **Lower tensile residual stress**	676.965	**240,705**	0.20	**217,027**	0.08
38	RBW2_3.2	24	0.3	112,464	Side 2 in tension, **Higher tensile residual stress**	902.62	**52,692**	-0.53	**70,014**	-0.38
39	RBW2_3.3	24	0.3	183,223	Side 1 in tension, **Lower tensile residual stress**	902.62	**92,983**	-0.49	**87,739**	-0.52

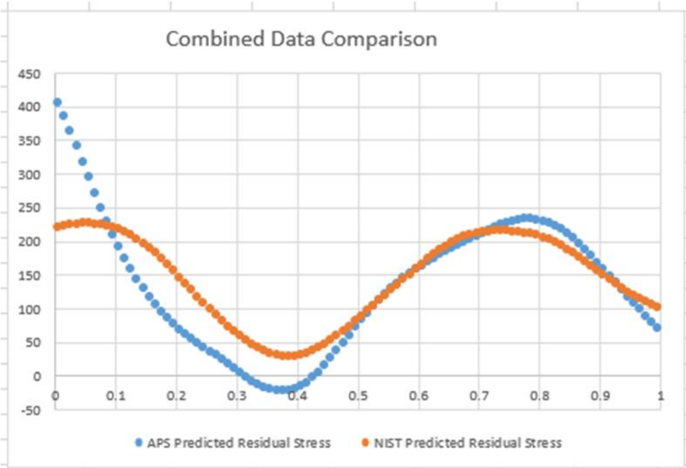




NIST residual stress distribution *may* give *slightly* better correlation to test data

Questions?

Total Fatigue Life: Crack Initiation and Crack Propagation Analysis… Whole Life
Evaluate Residual Stress Distributions Obtained by Two Different Methods



Doesn't make much difference which distribution or direction of distribution is used

Specimen	Designation	Load (kN)	R Ratio (σ_{min} / σ_{max})	Cycles	Notes	Stress Mpa	APS		NIST	
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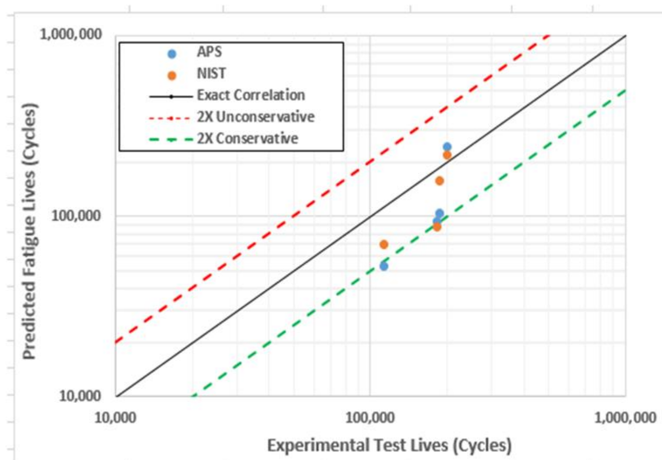
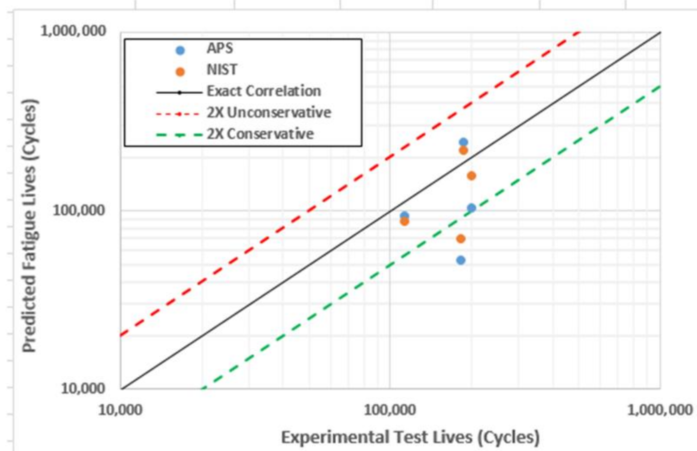
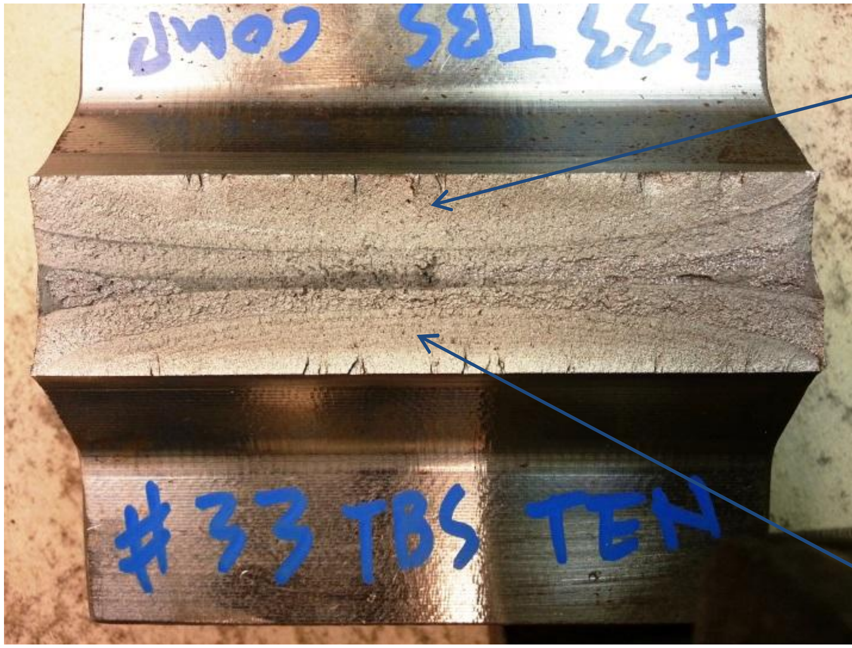


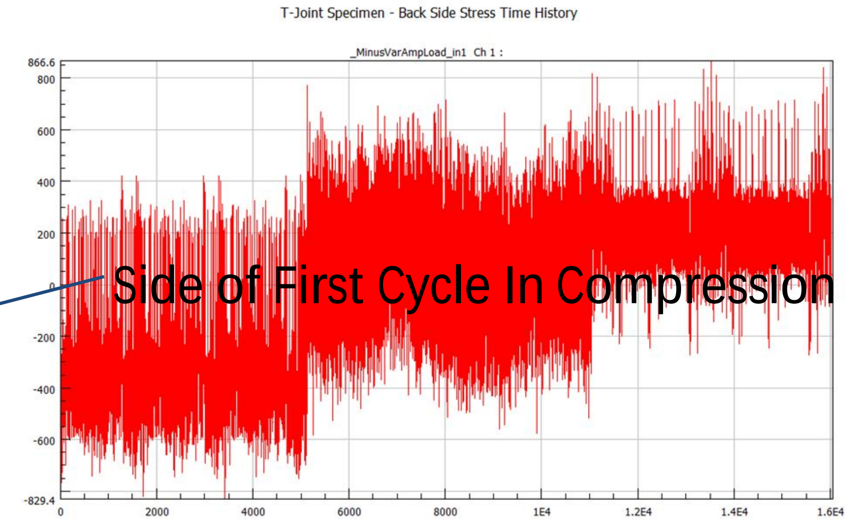
Specimen	Designation	Load (kN)	R Ratio (σ_{min} / σ_{max})	Cycles	Notes	Stress Mpa	APS		NIST	
36	RBW2_2.2	18	0.1	185,863	**Side 2 in tension**, Higher tensile residual stress	676.965	240,705	0.30	217,027	0.17
37	RBW2_2.3	18	0.1	201,168	**Side 1 in tension**, Lower tensile residual stress	676.965	104,616	-0.48	156,086	-0.22
38	RBW2_3.2	24	0.3	112,464	**Side 2 in tension**, Higher tensile residual stress	902.62	92,983	-0.17	87,739	-0.22
39	RBW2_3.3	24	0.3	183,223	**Side 1 in tension**, Lower tensile residual stress	902.62	52,692	-0.71	70,014	-0.62

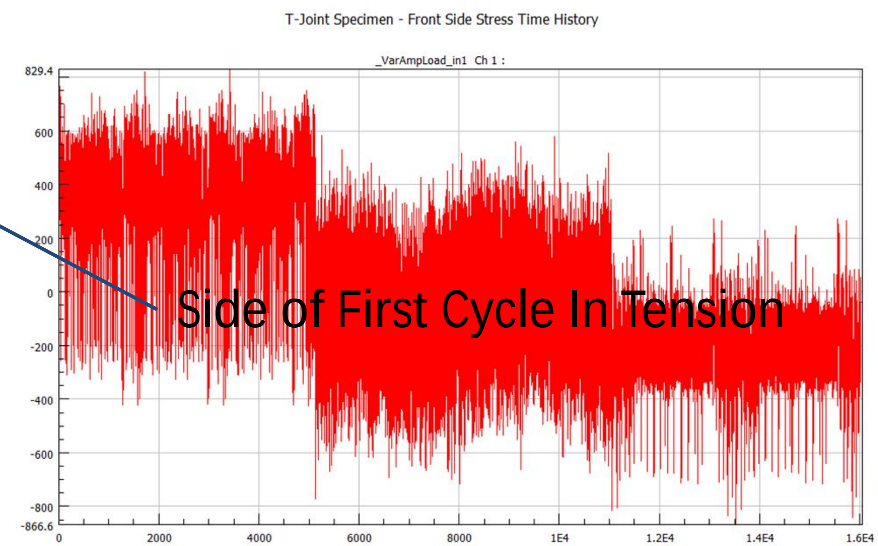


EXPERIMENTAL TEST

The variable amplitude test specimen has cracks growing simultaneously from opposite sides toward each other. Each crack is driven by the inverse of the load history from the other side.

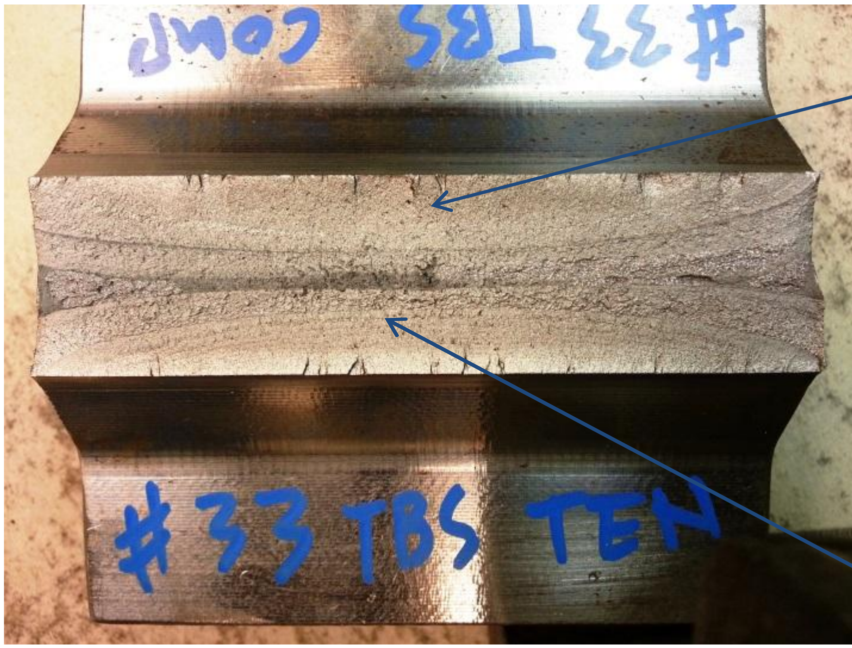


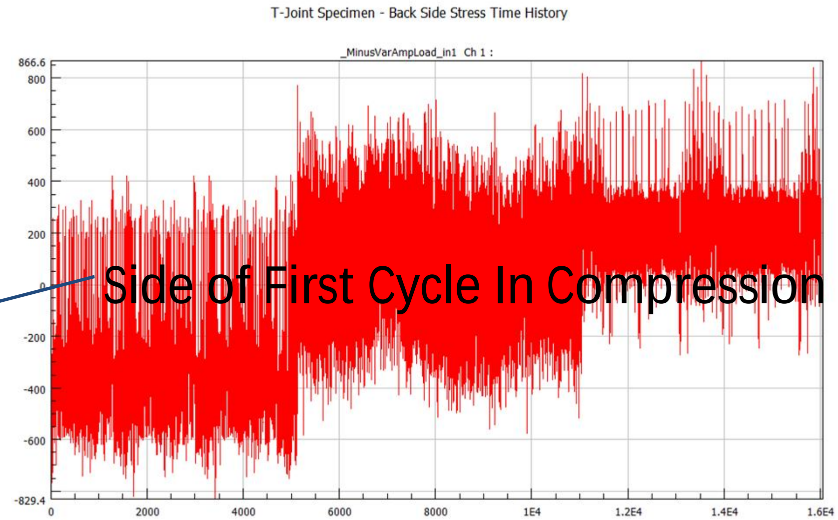




WHOLE LIFE FATIGUE ANALYSIS

The variable amplitude test specimen is analyzed as a crack growing from only one side of the specimen. The analysis predicts the first cycle in compression side of the specimen to have the shortest fatigue life.





A single crack prediction (on left) would un-conservatively predict an opposing crack test (on right)?