Application of the Local Stress-Strain-Life Approach to a High-Low Loading Test Series of a Coiled Tubing Steel

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Report to API 17G2 committee
Nov. 4 2020

Test data is described in Ref.:

C.D Bridge, “Combining Elastic and Plastic Fatigue Damage in Coiled Tubing,” Soc. Petro. Engr. SPE 142427, Presented at the SPE/ICoTA Coiled Tubing and Well Intervention Conf. The Woodlands, Texas, USA, 5–6 April 2011.

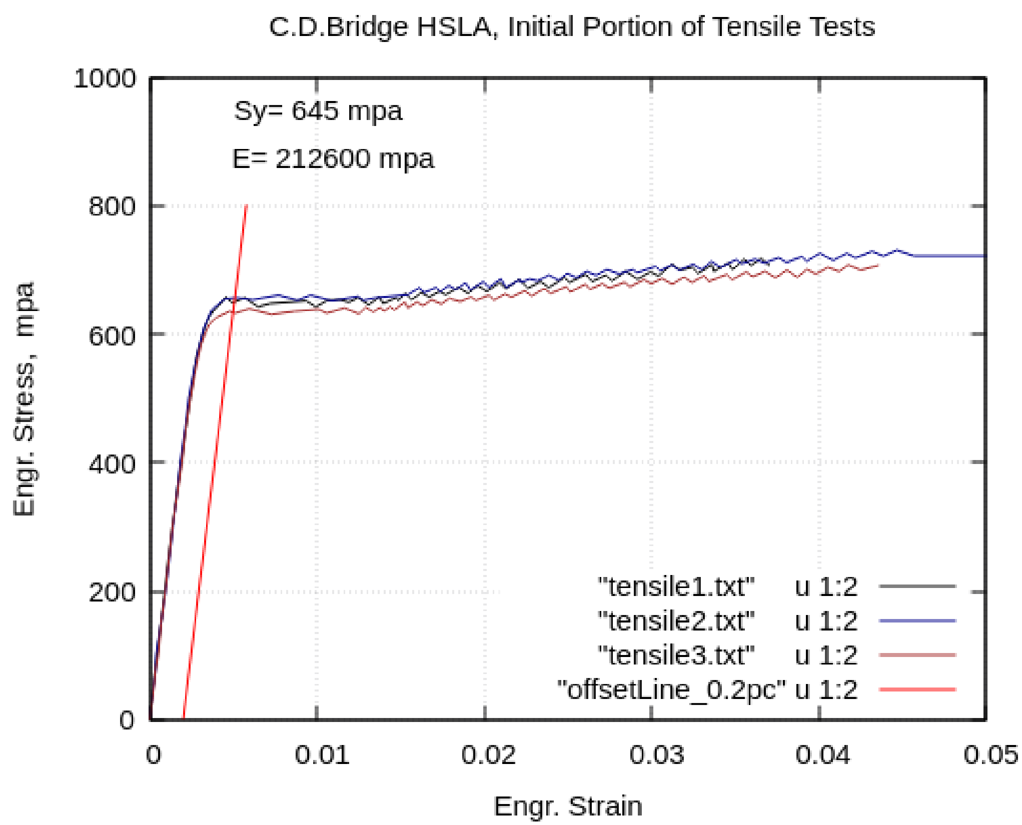
Material

In the SPE-142427 paper the material is stated to be “ASTM A606 steel”

There are 4 or 5 types of A606 steels of which Type V is an HSLA with addition of Cu= 0.65-0.98 wt.% and other elements. The additional Cu is added to create a weathering steel, like Corten(trade name). Since the paper concerns Coiled Tubing we can assume that corrosion resistance is fairly importent, thus the steel is probably ASTM A606 Type V.

Most of the A606 steel types have a minimum yield specification of Sy=50ksi and min. ultimate Su=70ksi.

The material from Ref.[1] however has an Sy= 94ksi (645 mpa) Ref.[5]



The fatigue data set at:

https://fde.uwaterloo.ca/Fde/Materials/Steel/Hsla/watsonVAN80-non+iniOS.html

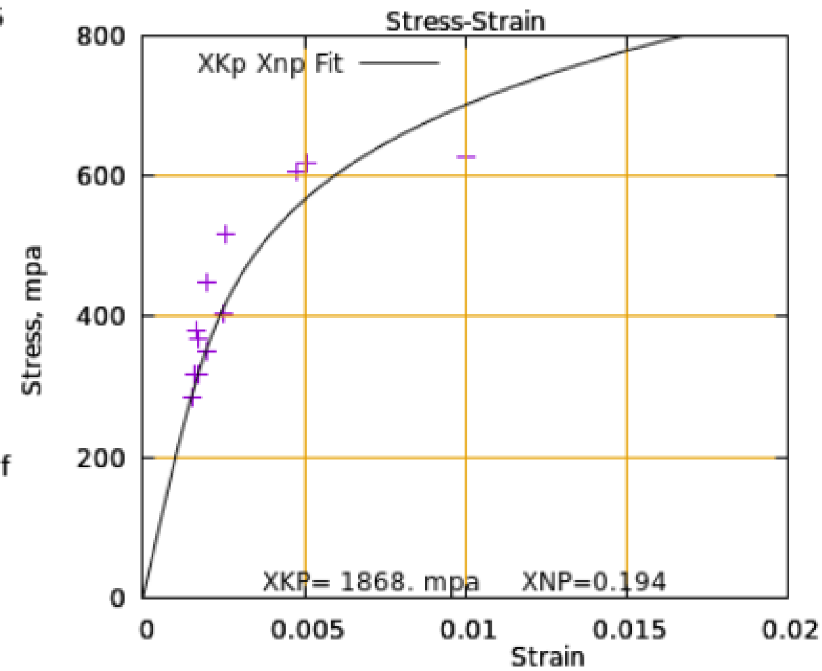
is depicted on the next page.

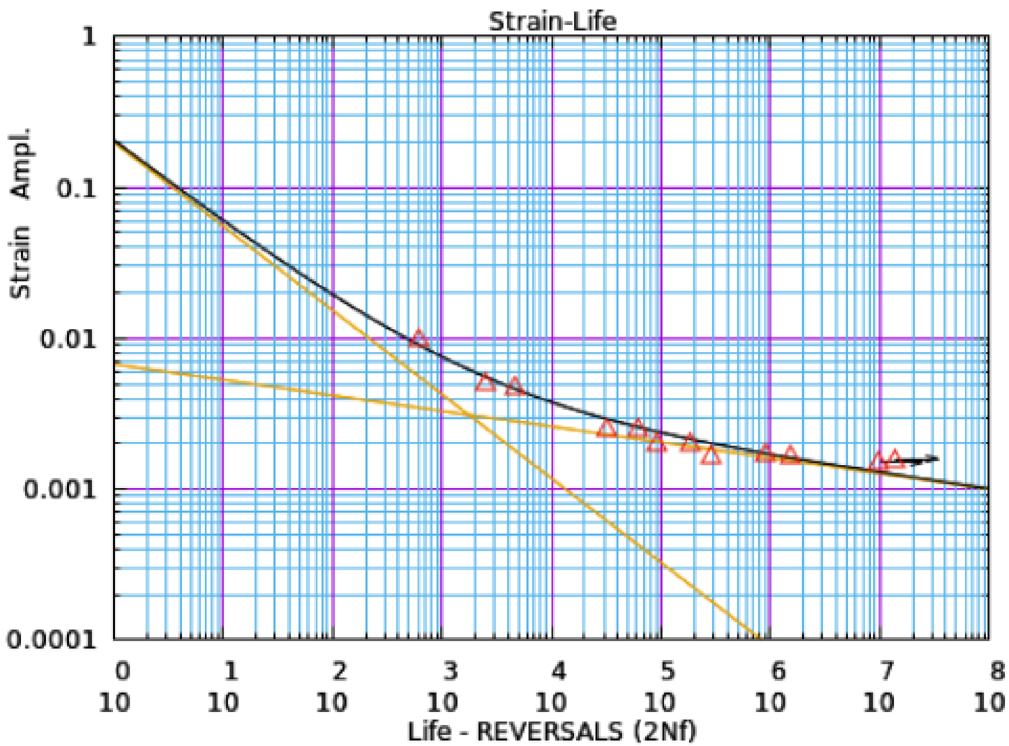
SAE980K VAN80 HSLA-550 BHN= 225

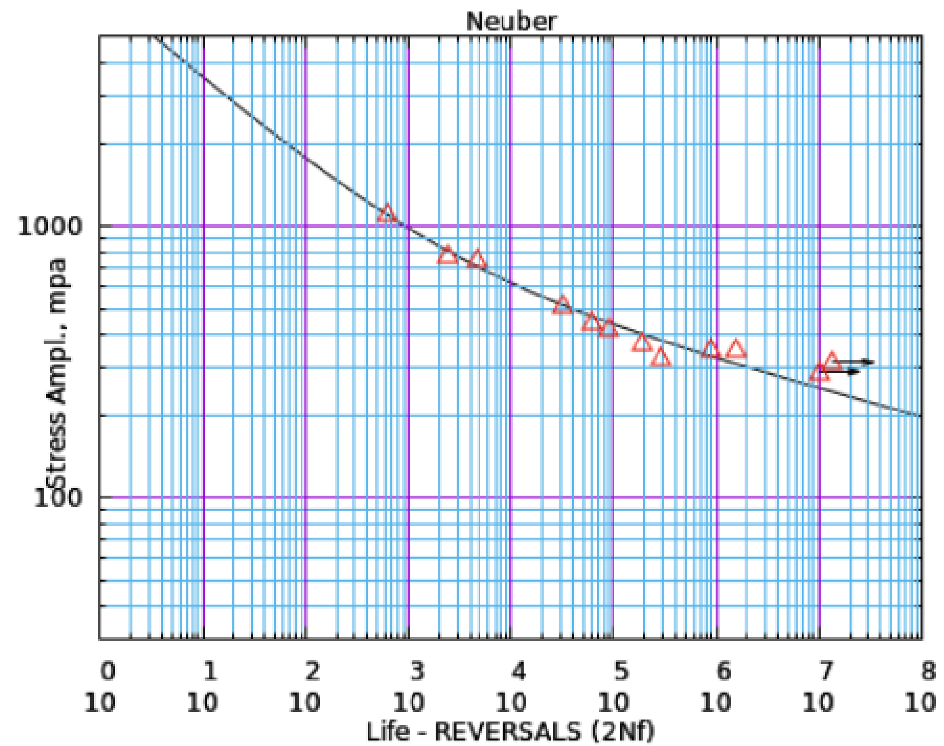
```
# SAE 980X HSLA-550 VAN80  machined from 5/16inch plate channels.
# Some specimens were initially overstrained 10 cycles +-1.0% strain
# (as tabulated below)
# 0.145C wt% 1.25Mn .01P .011S .38Si .06Cu .033Ni .04Cr .056Al .008Mo .12V
# Ref.: P.Watson and T.H.Topper, 'An Evaluation of the Fatigue Performance
# of Automotive Steels,' SAE Paper 710597, Montreal Que.,  Jun.7-11 1971
# Data digitized from graphs and may contain errors.
```

```
Properties:          Monotonic                    Cyclic
ELAS. MOD.= 28717. KSI    198000. MPA
YIELD 0.2%=        84. KSI,       579. MPA
ULT. STRG.=        99. KSI,       686. MPA      F. STRG COEF=   193.4 KSI,   1334.MPA
K=                 0.0 KSI,         0. MPA     F.STRG EXP,     b=-0.1034
N=              0.0000                          FAT DUCT COEF=   0.1993
%RED. in AREA =    68.0                         F.DUCT EXP,    c=-0.5571
FRAC. Stress=      176.9 KSI,    1220. MPA      Exp Cyc Yld  =   82. Ksi,    568.MPA
FRAC. Strain=   1.150
No. data points=   12
```

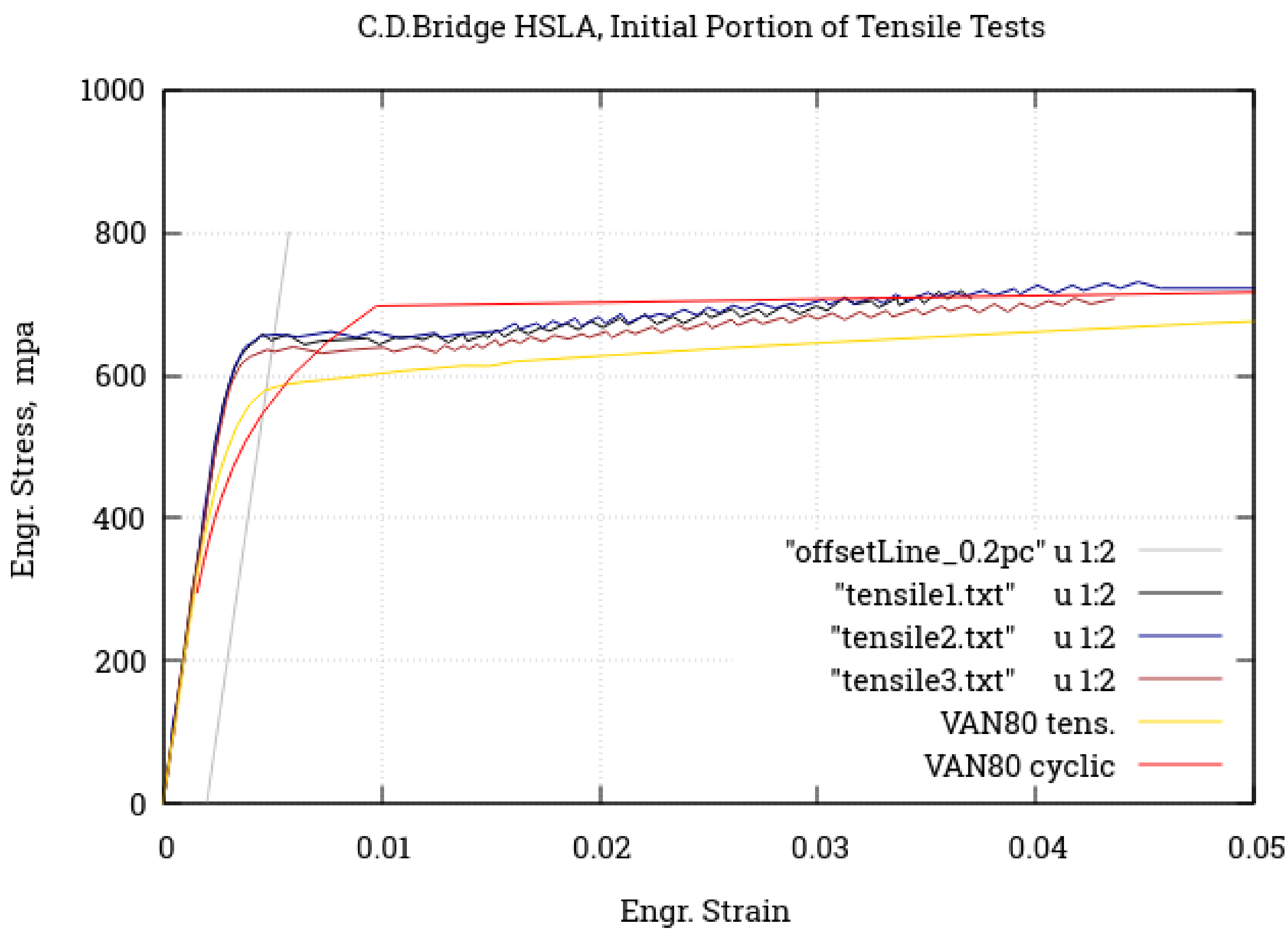
Background: http://fde.uwaterloo.ca/FatigueClass/Chap7Notches/chap7sec2-DbaseFiles.pdf



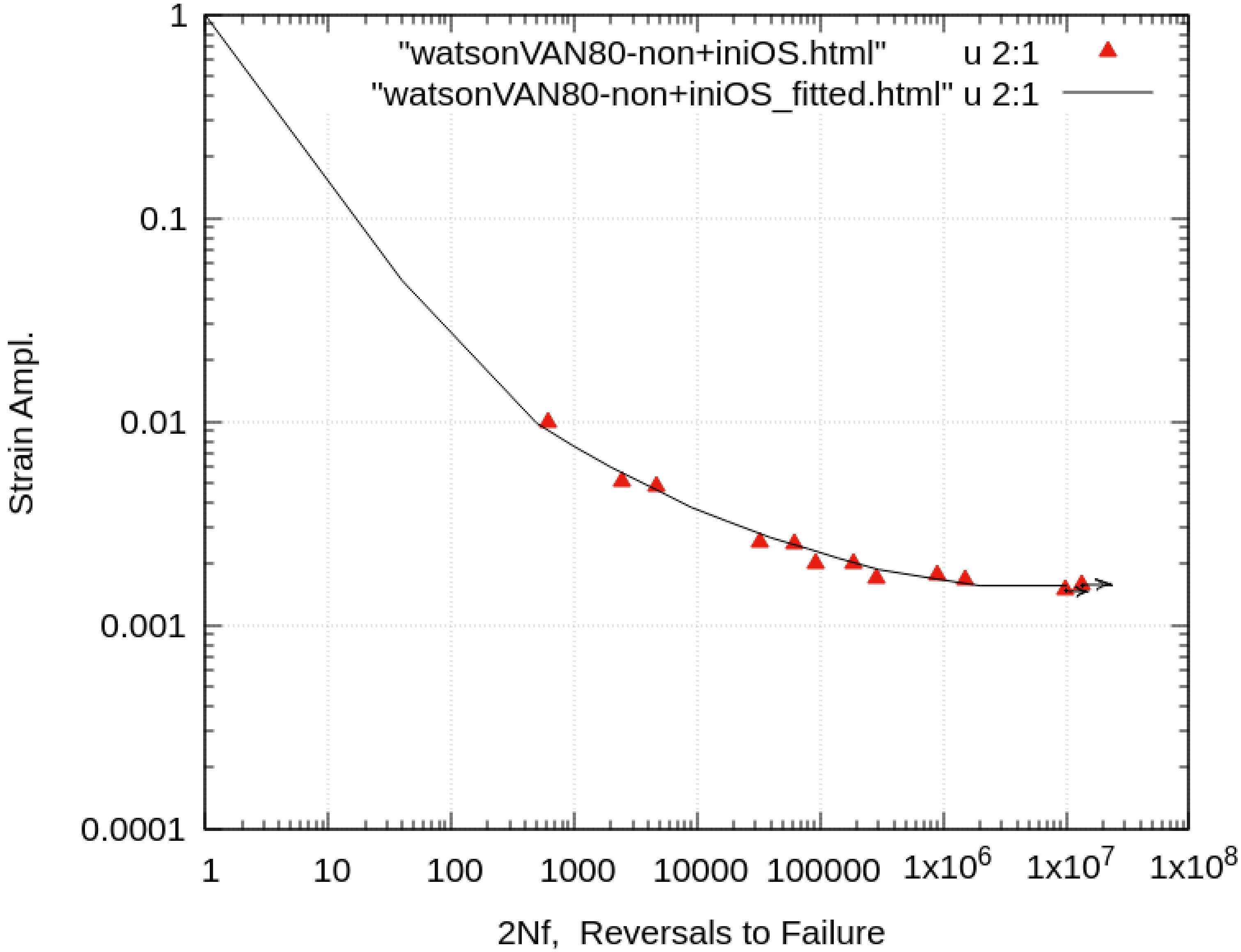




Tensile data from Ref.[5] and the VAN80 tensile and cyclic stress-strain curves are comparable. It appears that we can use the VAN80 data set to make simulated fatigue life calculations.

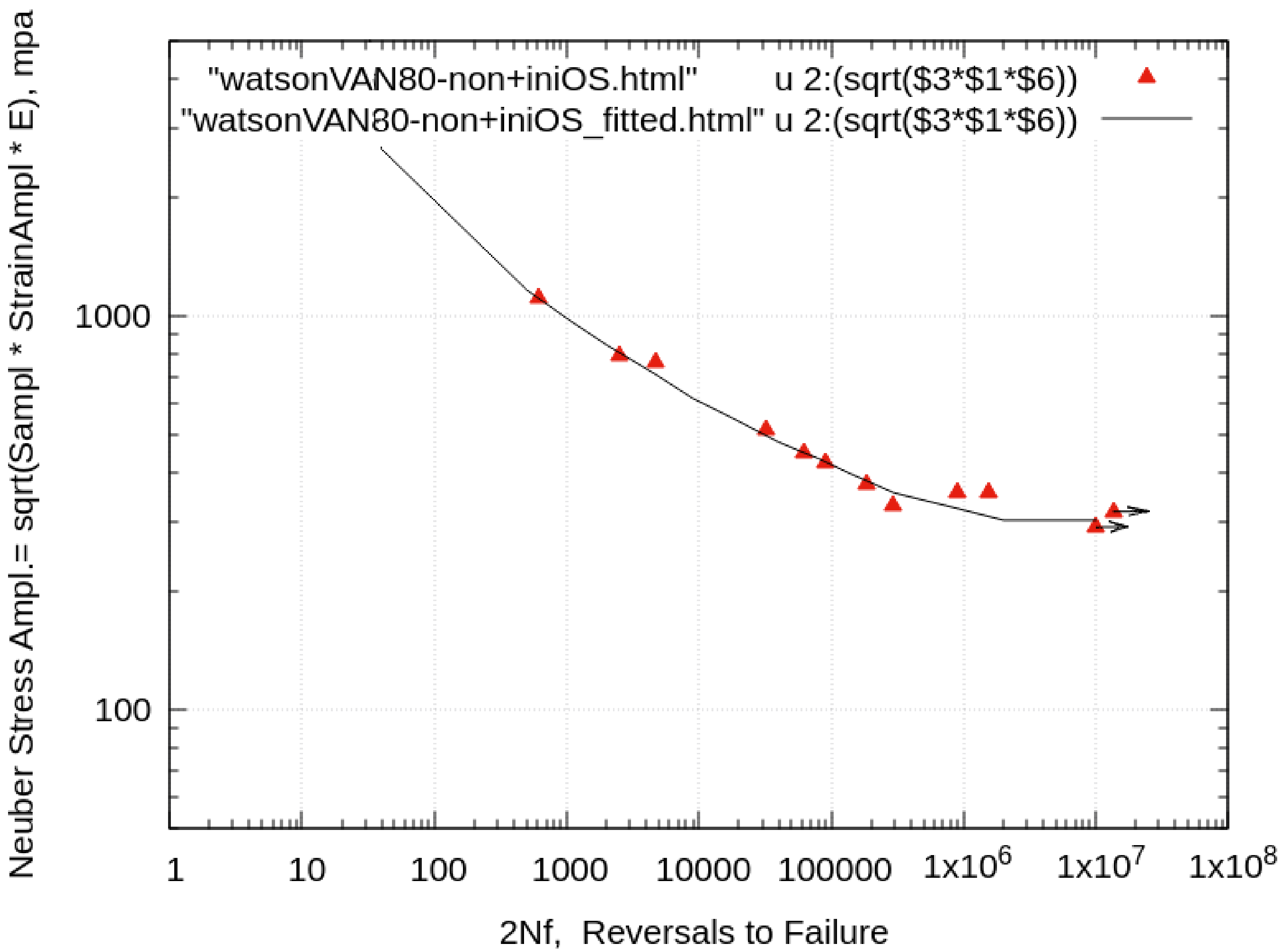


The fatigue data set is shown in the figure along with a “fitted” line shown in black. For fatigue damage counting of coiled tubing strain histories a Periodic Overstrain data set would be more appropriate, but such is not available.



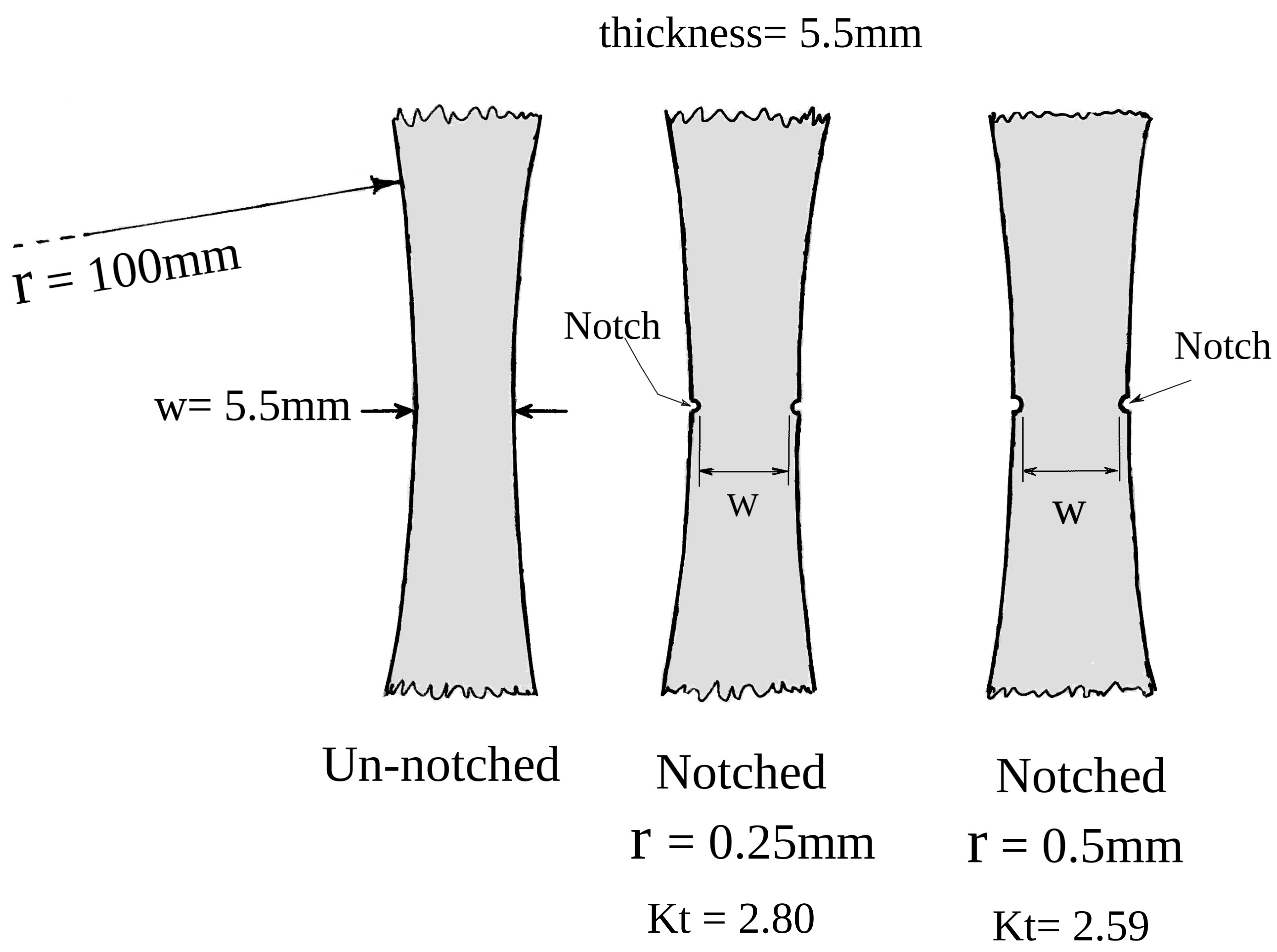
A Neuber stress plot can be used to translate elastic nominal stress to life estimates and to allow Y axis inputs from local stress-strain hysteresis loops containing a mean stress.

Neuber Stress Plot



For explanation of a Neuber Stress Plot please see:
https://fde.uwaterloo.ca/Fde/Notches.new/neuberStress4AISIpt1.pdf

Test Specimens



Double edge notched specimen widths between
notch roots same as un-notched specimen w = 5.5 mm
Notch shapes are circular
Kt computed from Ref. [2]

Test Loads or Strains

The big cycles tests were performed in strain control with a 3mm resistance strain gage glued to the specimen at the minimum cross-section[5]. Presumably this was a type of “open loop strain control”.

The strain limits for the big cycles were $e_{max} = 0.018$ and $e_{min} = 0$

were e is strain.

The small cycles were performed in load control with stress limits

$S_{max} = P_{max}/A_{net}$ of values 300 and 400 mpa

where S_{max} is net section stress, P_{max} is load and A_{net} is assumed to be the minimum cross-section area between the notch roots.

Test Results from [1]

Table 1 Un-notched Constant Ampl. Tests

StrainMax	StrainMin	StressMax	StressMin	Test Nf	Simul_Nf	Comment
0.018	0			519	349	Strain-Life
0.0018	0.0001	300	0	>1M	Infinity	SWT
0.0101	0.0081	400	0	>1M	Infinity	SWT

!NAME= SAE980K #NAME= VAN80 #NAME= HSLA-550 #NAME= Steel #Sy= 579. 0.2pc offset = 84 ksi #Su= 686. mpa #BHN= 225.
!read_a_line: # #MagFactor 1.3 1200 -450 1

Nominal and Local Stress-Strain:

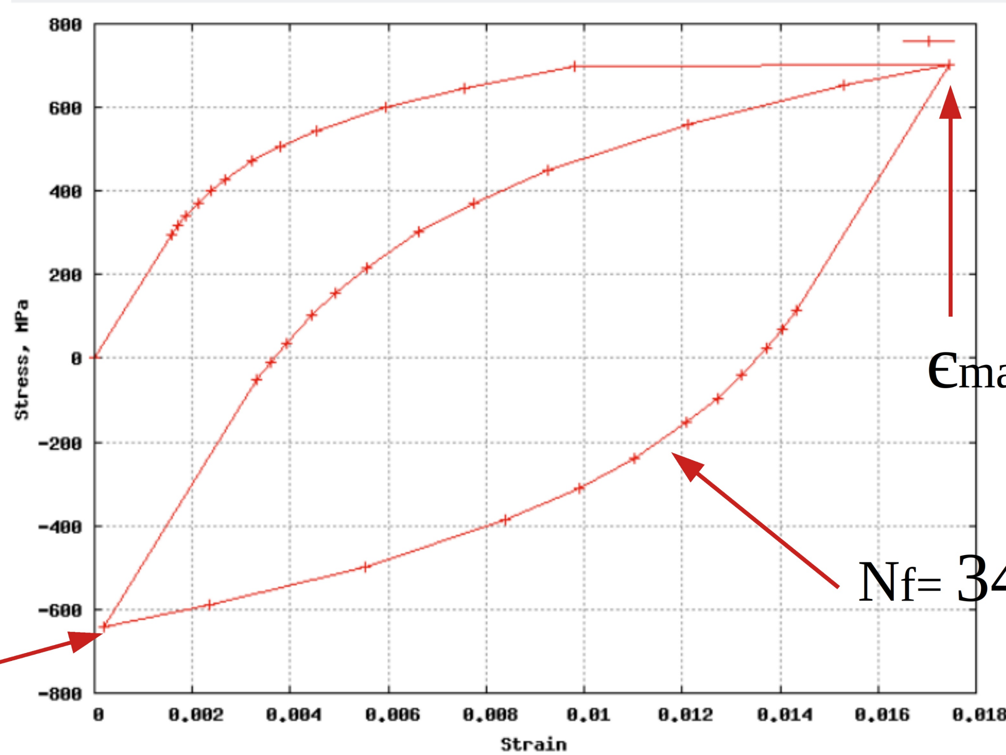
```
xcalc2 Loop   Smax    Smin        N  Sigmax  Sigmin Delta Epsmax Epsmin DeltaEps  %Eps %SWaT %Sts %Morr %Goodm
xcalc2    1  1560.0  -585.0       1.0    704.  -641. 1345. 0.01746 0.00019 0.01727 100.0 100.0 100.0 100.0 100.0
```

Life Predictions (history repetitions):

```
xcalc3  StrainLife_Reps SWaT_Life_Reps StressLife_Reps   Morrow_Reps   Goodman_Reps (Reps= Repetions)
xcalc3       349.2           317.8           349.2           274.2          90.4
```

Local Stress and Strain Response:

Simulation Predictions



Єmax=0.018

Nf= 349

Єmin= 0

Un-notched, small cycle simulations

Used SWT to correct for mean stress

#read_a_line: # #MagFactor 1 445 20 1

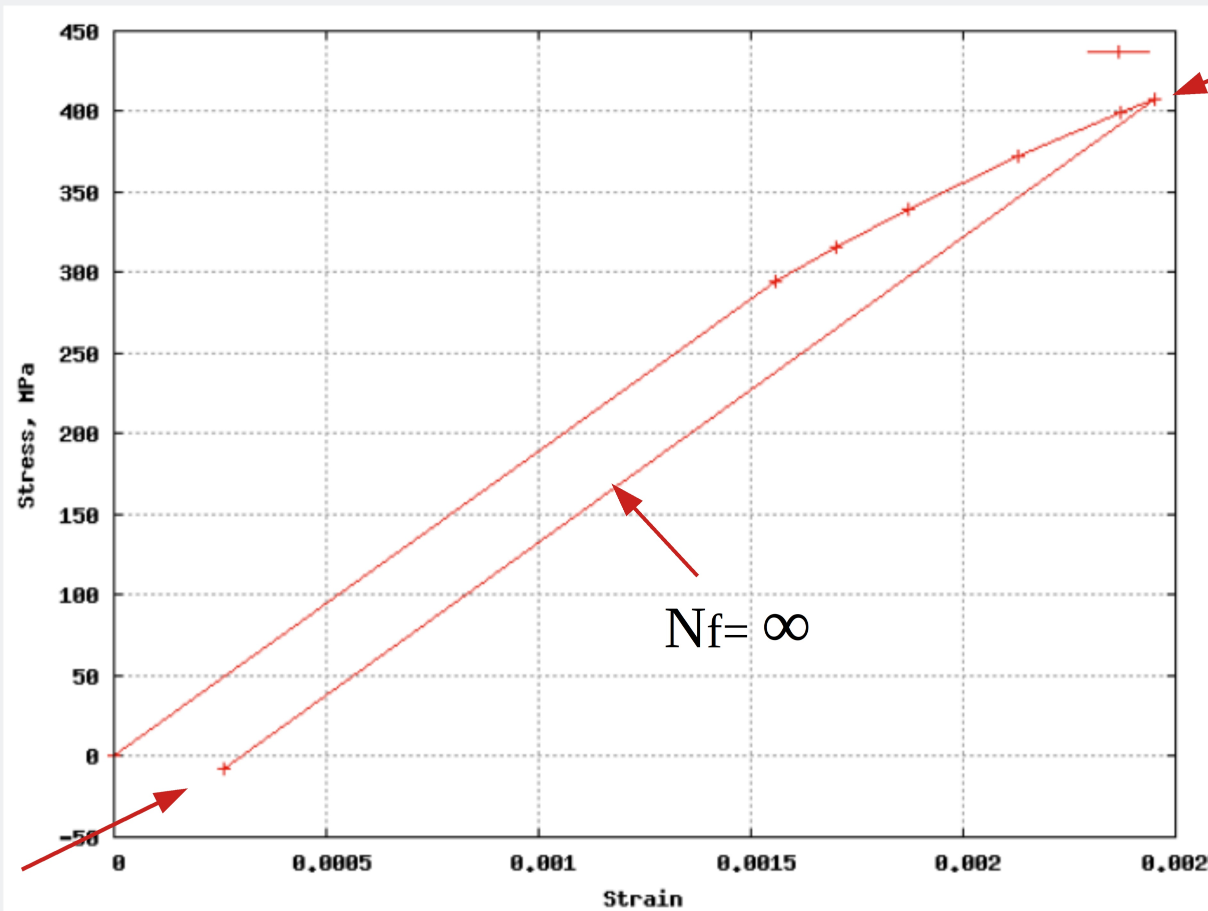
Nominal and Local Stress-Strain:

```
#xcalc2 Loop   Smax    Smin        N  Sigmax  Sigmin Delta Epsmax Epsmin DeltaEps   %Eps  %SWaT  %Sts  %Morr  %Goodm
#xcalc2    1   445.0    20.0       1.0   408.     -8.  415. 0.00245 0.00026 0.00220   0.0    0.0   0.0    0.0    0.0
```

Life Predictions (history repetitions):

```
#xcalc3  StrainLife_Reps SWaT_Life_Reps StressLife_Reps   Morrow_Reps   Goodman_Reps (Reps= Repetions)
#xcalc3  Infinity        Infinity        Infinity          Infinity       Infinity
```

Local Stress and Strain Response:



σmax=400 mpa

Nf= ∞

σmin=0

(Both small cycles were fully elastic)

Test with smaller
Smax=300
also Nf=∞

Un-notched Specimen Test Results from [1] plotted vs HSLA VAN80 data

For the small elastic cycles with mean stress we need to use a Neuber Stress plot to compare the test data. Thus

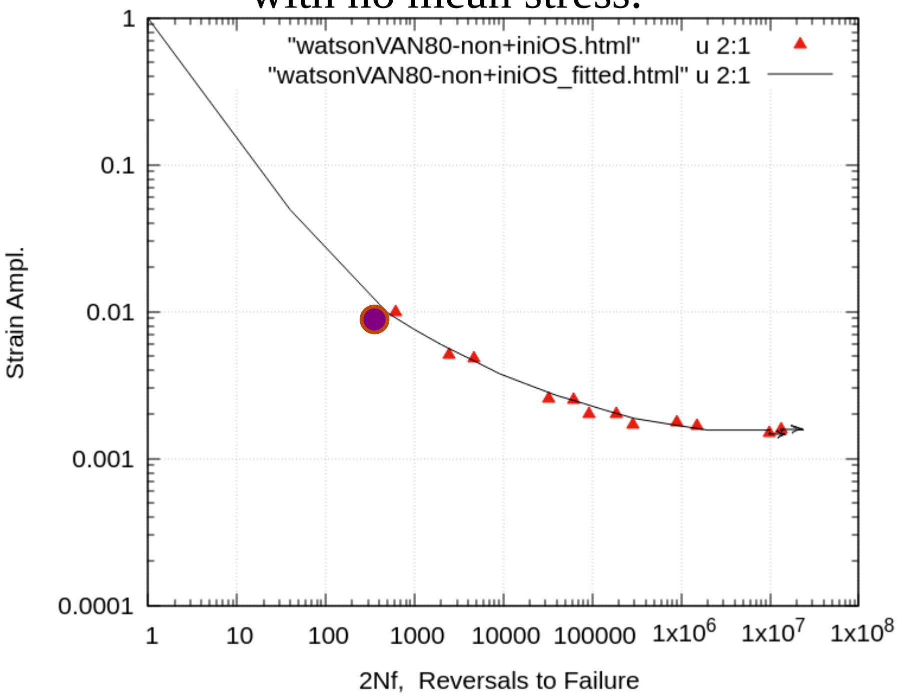
$$\sigma_{\text{equivAmpl.}} = \sqrt{(\sigma_{\max} * \sigma_{\text{ampl.}})}$$

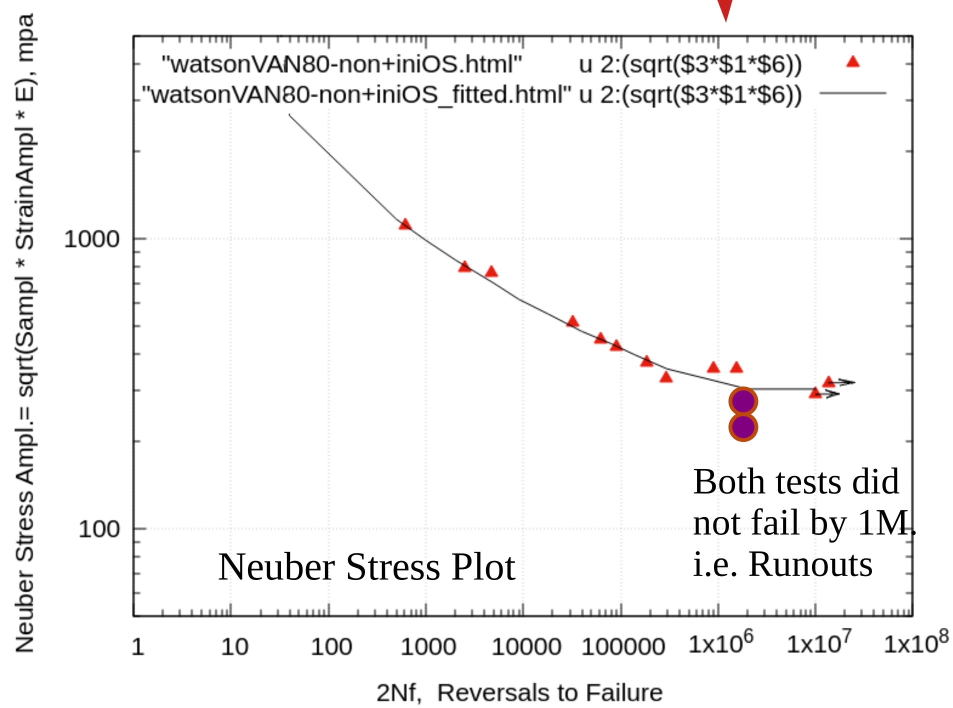
300 → sqrt(300 * 150) = 212 mpa

400 → sqrt(400 * 200) = 283 mpa

The large cycles have a strain amplitude 1/2 of 1.8% which is Strain Ampl. = 0.009

Fully reversed strain control tests with no mean stress.





● CA Tests from Ref. [1]

Table 2: Test results for Notched (r =0.25mm) specimens and computed damage fractions and Linear Damage (Miner's sum) small cycle(Smax=300mpa) life predictions.

N2f

No. of Big Cyles n1	Test No. of Small Cycles n2	Average	D1=n1 / N1f Big_Damage	n2= (1-D1) * N2f Expected Small n2 (Miner's Sum)
0	394647			
0	315459	340809	0	340809
0	312321			
4	311406		0.037	328302
11	279851		0.101	306415
11	174821		0.101	306415
16	214699		0.147	290782
22	253656		0.202	272022
33	227646		0.303	237628
38	229869		0.349	221995
55	148862		0.505	168841
71	141503		0.651	118814
82	80237		0.752	84421
102	0			
116	0	109	1	

Small Cycles only tests

High-Low Tests

Large Cycles only tests

From Ref.[1] figure 6

N1f

Table 3: Test results for Notched (r =0.5mm) specimens and computed damage fractions and Miner's sum small cycle(Smax= 300mpa) life predictions.

No. of Big Cyles n1	Test No. of Small Cycles n2	~Average	D1=n1 / N1f Big_Damage	n2= (1-D1) * N2f Expected Small n2 (Miner's Sum)
0	182556	182556	0	182556
4	221510		0.047	174065
8	196413		0.093	165574
12	156548		0.140	157083
17	130160		0.198	146469
26	104516		0.302	127365
29	117442		0.337	120996
42	97157		0.488	93401
53	92929		0.616	70051
62	55841		0.721	50946
82	0			
91	0	86	1	

From Ref.[1] figure 6

Table 4: Test results for Notched (r =0.25mm) specimens and computed damage fractions and Miner's sum small cycle(Smax=400mpa) life predictions.

No. of Big Cyles n1	Test No. of Small Cycles n2	Average	D1=n1 / N1f Big_Damage	n2= (1-D1) * N2f Expected Small n2 (Miner's Sum)
0	76050	76050	0	76050
11	56685		0.097	68647
22	47657		0.195	61244
33	22017		0.292	53841
55	15959		0.487	39035
82	16923		0.726	20863
109	0			
116	0	113	1	

From Ref.[1] figure 6

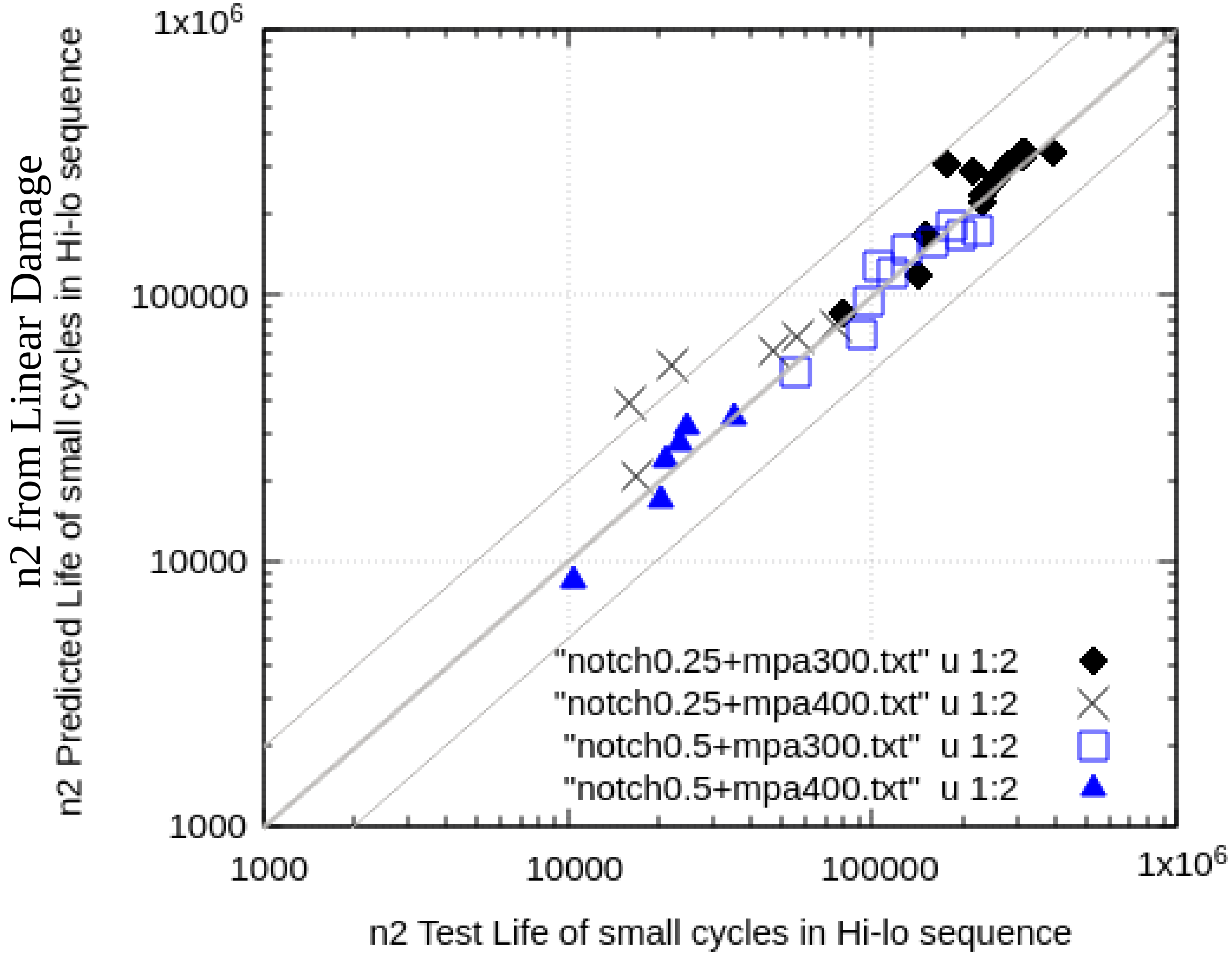
Table 5: Test results for Notched (r =0.5mm) specimens and computed damage fractions and Miner's sum small cycle(S_{max}=400mpa) life predictions.

No. of Big Cyles n1	Test No. of Small Cycles n2	Average	D1=n1 / N1f Big_Damage	n2= (1-D1) * N2f Expected Small n2 (Miner's Sum)
0	34887	34877		34877
8	24747		0.096	31515
17	23469		0.205	27734
26	21083		0.313	23952
43	20369		0.518	16808
63	10432		0.759	8404
80	0			
86	0	83		

From Ref.[1]
figure 6

From Tables 2 to 5 one can compare the High-Low test small cycle lives with the Linear Damage "Palmgren-Miner" rule computed n2 lives by first computing the damage of the large cycles D1 and then the n2 value given the "left-over" damage fraction. The numeric results are shown in the tables.

The plot below compares the Test n2 with the Linear Damage n2 prediction. Except for two points the results are quite satisfactory.



Simulating the Notched Specimen Tests

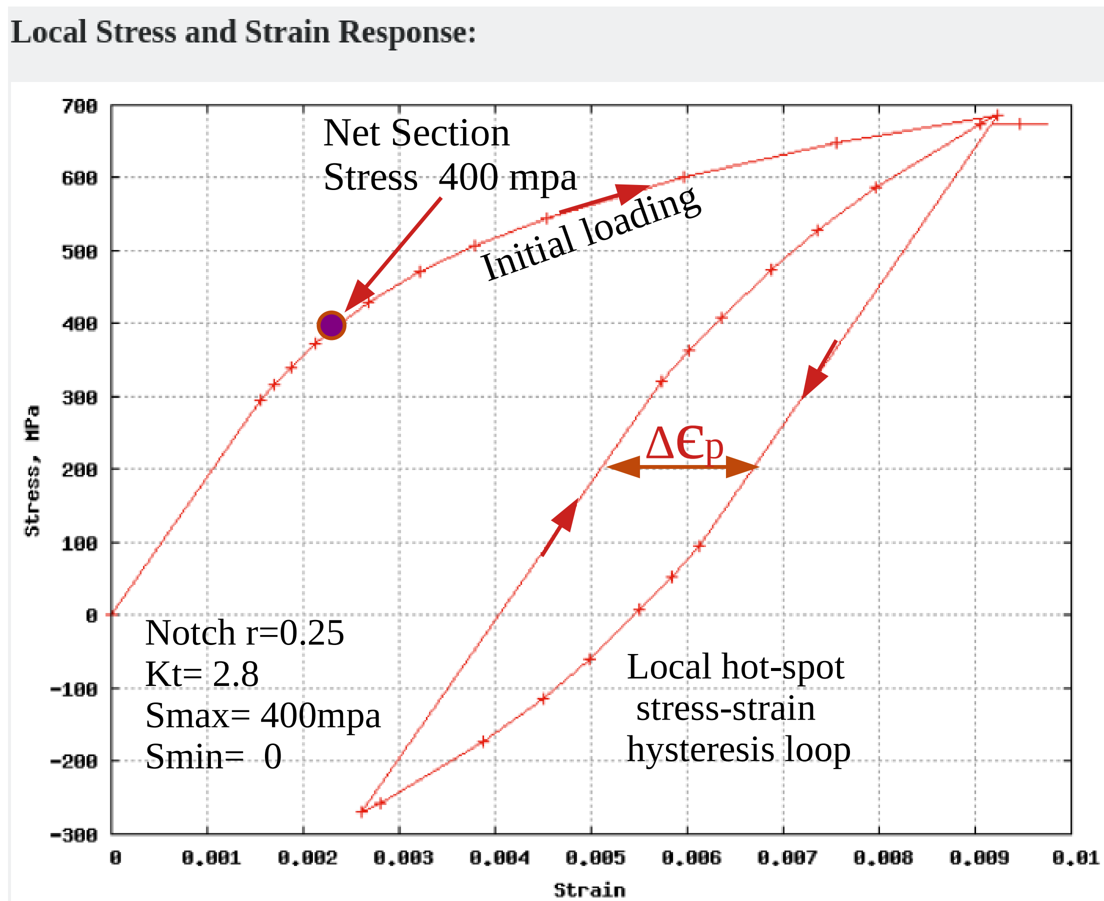
The double notched specimen with r=0.25mm has a computed stress Concentration Factor Kt = 2.8 The specimens with r=0.5mm have a Kt = 2.6 (from Ref.[2])

Normally one would use the Neuber Plasticity Correction [4] to transform the elastic nominal stress away from the notch to compute the local stress and strain at the notch root. These local stresses and strains would then be used to compute crack initiation life using the stress-strain-life curves shown on the previous pages.

In the example at the right the fatigue calculator

VAN80 fatigue Calculator with Kt

has been use to compute the local stress-strain response at the root of the 0.25mm notch when subjected to only S_{max}=400 and S_{min}=0 mpa cycles.



Test :
r =0.25 Nf= 75,217

Simulation
Nf= 7,934

For a plastic strain range of $\Delta\epsilon_p = 0.0017$ we can estimate the cyclic mean stress relaxation

using $\Delta\epsilon_p/2 = 0.00085$

Result relaxation in about 50 cycles, thus no mean stress correction is necessary

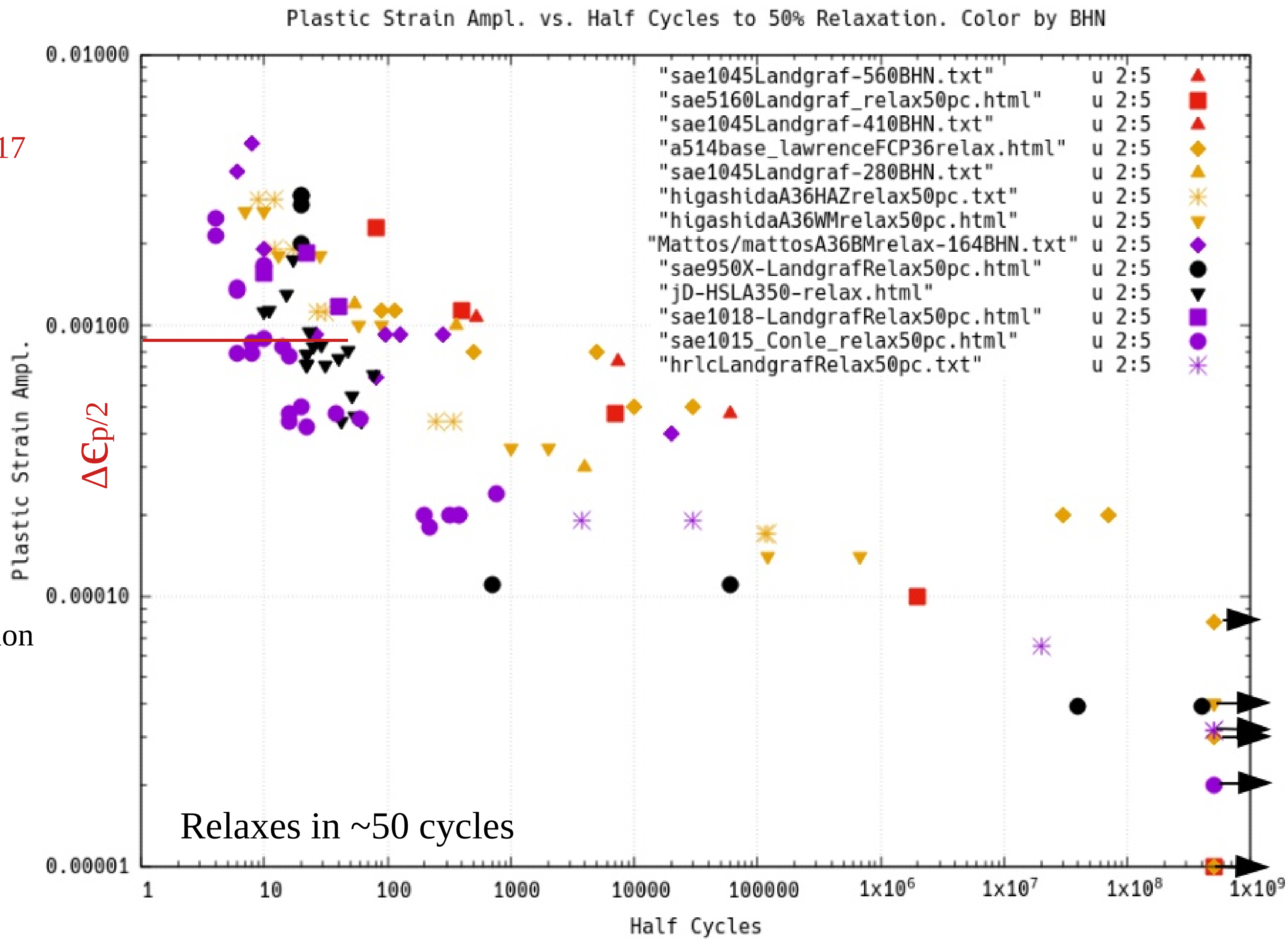


Figure from:
https://fde.uwaterloo.ca/Fde/Articles/fde2019RelaxPres4Web.pdf

Similarly for:

Notch r=0.5mm
Kt= 2.6
Smax= 400mpa
Smin= 0

#read_a_line: # #MagFactor 2.6 400 0 1

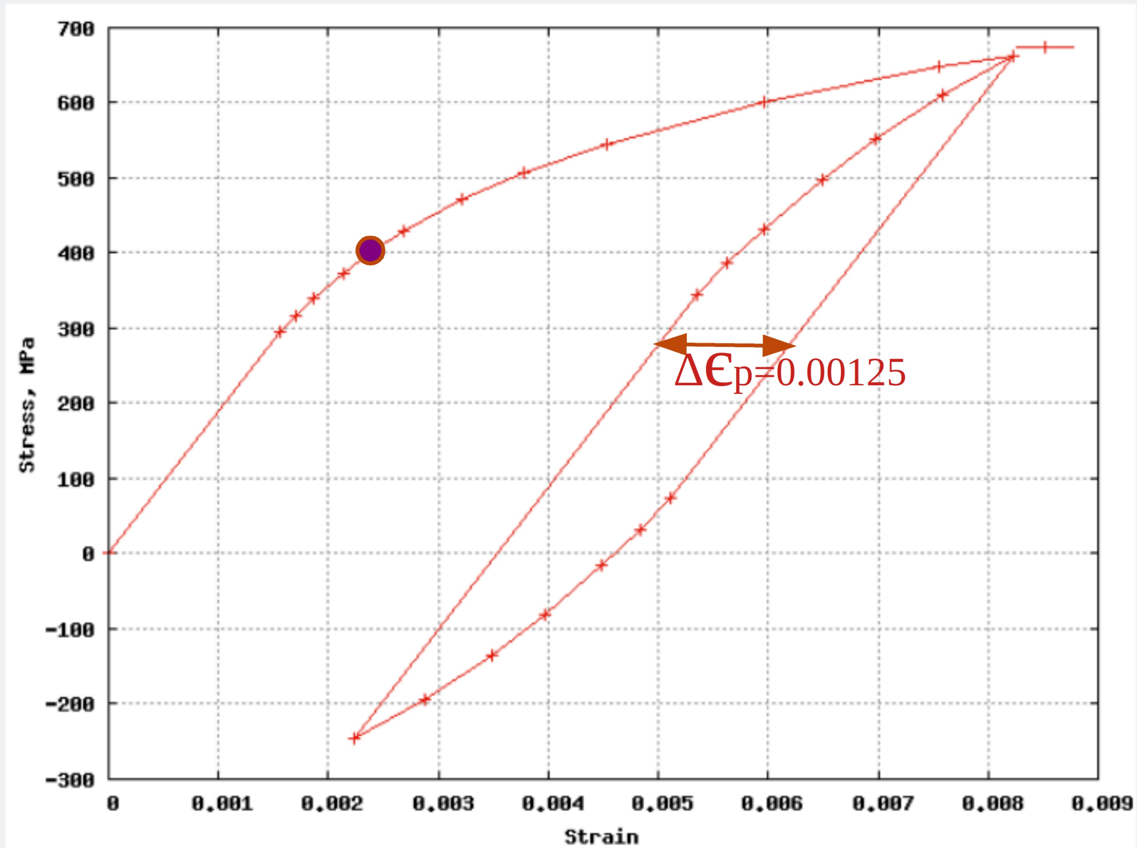
Nominal and Local Stress-Strain:

```
#xcalc2 Loop    Smax     Smin         N  Sigmax  Sigmin Delta Epsmax Epsmin DeltaEps  %Eps %SWaT %Sts %Morr %Goodm
#xcalc2    1  1040.0      0.0        1.0    663.  -246.  910. 0.00823 0.00223 0.00601 100.0 100.0 100.0 100.0 100.0
```

Life Predictions (history repetitions):

```
#xcalc3  StrainLife_Reps SWaT_Life_Reps StressLife_Reps    Morrow_Reps    Goodman_Reps (Reps= Repetions)
#xcalc3     12196.5          4112.5         12196.5          2360.7           456.3
```

Local Stress and Strain Response:



Relaxes in
~50 -100 cycles

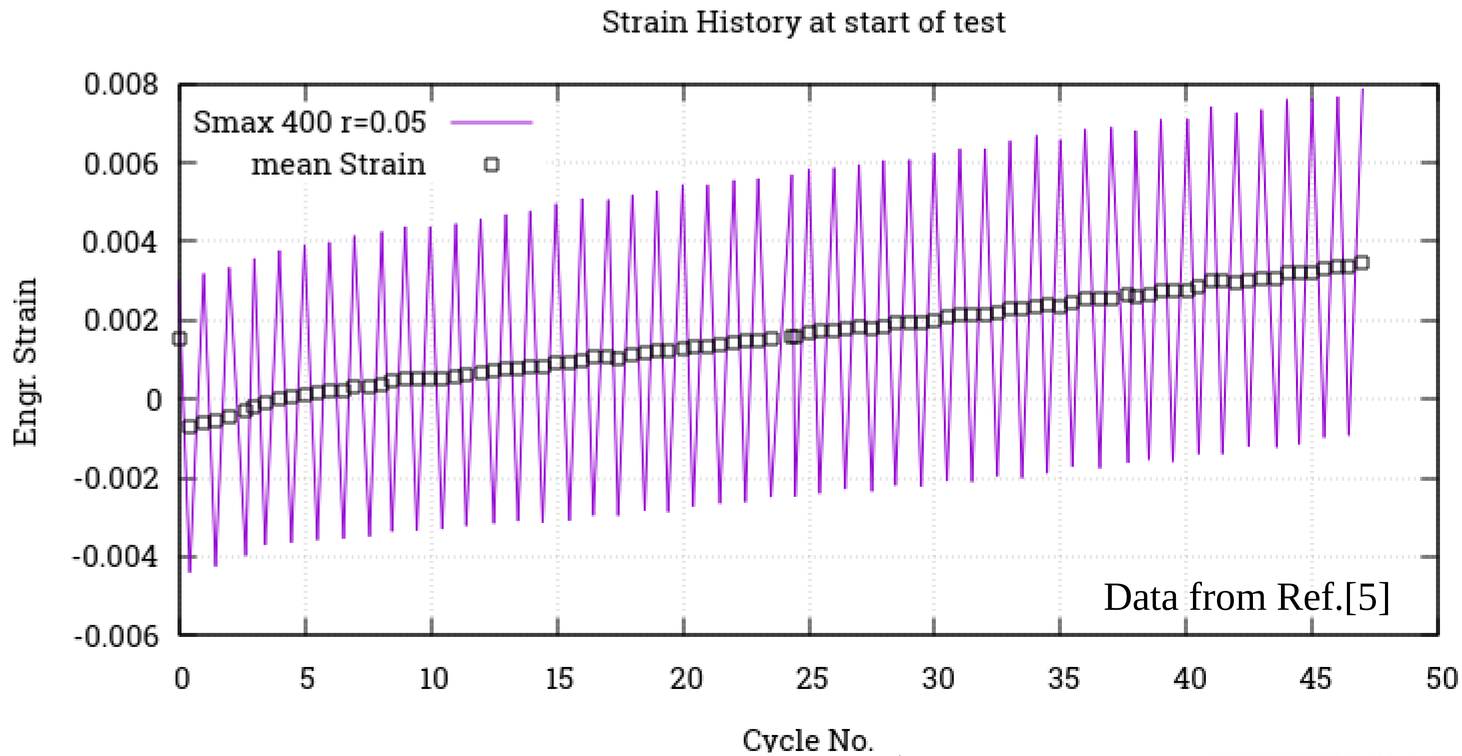
Test :
r= 0.5   Nf= 35,642

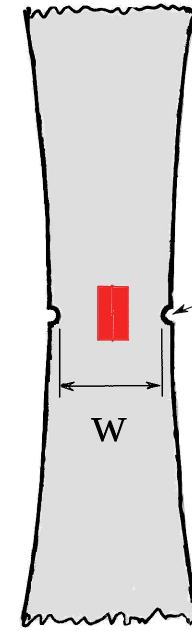
Simulation
Nf= 12,196

Compare Simulate vs. Test notched specimens
Const. Ampl. Loading

r	Kt	Smax	Smin	Test	Simul.	Simul.
mm		mpa	mpa	Nf	Δεp/2	Nf
0.25	2.8	400	0	75,217	.00085	7,934
0.25	2.8	300	0	341,000	.00025	48,472
0.50	2.6	400	0	35,642	.00063	12,196
0.50	2.6	300	0	182,500	.00015	47,700

Life predictions are factors of 3 to 10 conservative. This is unusual for the local stress strain approach and suggests that something in the notched specimen tests is not being accounted for in the simulations.





Notched

r = 0.5mm

Above graph shows the strain recorded during a r=0.5mm notched specimen test (Ref.[5])

Note that the strain gage as shown in red on the specimen extends above and below the notched minimum cross-section. Thus the strain in the minimum section is probably larger than shown in the history.

It appears that ratcheting of strain is taking place. i.e. the section is going fully plastic.

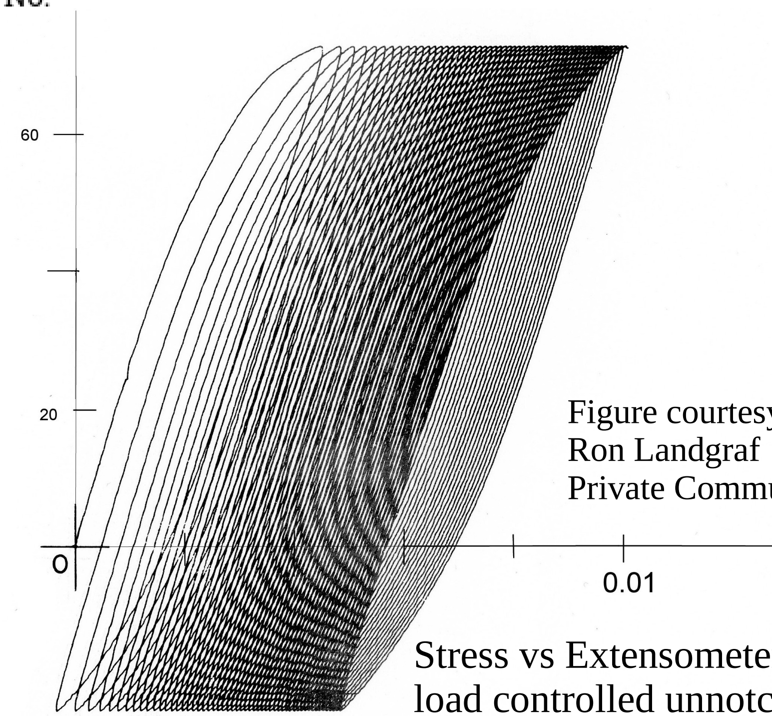


Figure courtesy of
Ron Landgraf
Private Communication

Stress vs Extensometer Strain during load controlled unnotched specimen test with mean load

The strain data displayed in the previous slide is rather confusing. i.e.: it is unclear how a 3mm strain gage responds if its central ~0.5mm experiences more strain than the rest of the gage's length.

It would be best to model this deformation with a non-linear FEA model such as Abaqus.

The effects of the net section plastic forming could result in a change of shape of the circular edge notches to elongated flat bottomed "U" shaped grooves. FEA models that can approximate the new shape, such as Abaqus, are beyond the present study but a rough estimate of the new shape Kt can be obtained by assuming the notches to be like a shoulder fillet (Ref.[2] pg.150)

Shoulder fillet of depths 0.25mm and 0.5mm for the specimen shapes in (slide 6) would have the following Kt_{net} with compared values for the original circular notch :

Root radius mm	Shoulder Kt	Circular Notch Kt
0.25	1.8	2.8
0.50	1.4	2.6

Since some shrinkage of material between the two edge notches can be expected the guesstimated value of a stretched circular notch lies probably beteen the two types shown above, thus for rough simulation purposes a value of $Kt_{net} = 1.6$ will be used to simulate all the notched specimen test results.

* Note: The following is strictly a rough approximation since the Neuber Plasticity Correction is not expected to be valid for full section plasticity !

Simulating the notched specimen large amplitude strain controlled tests

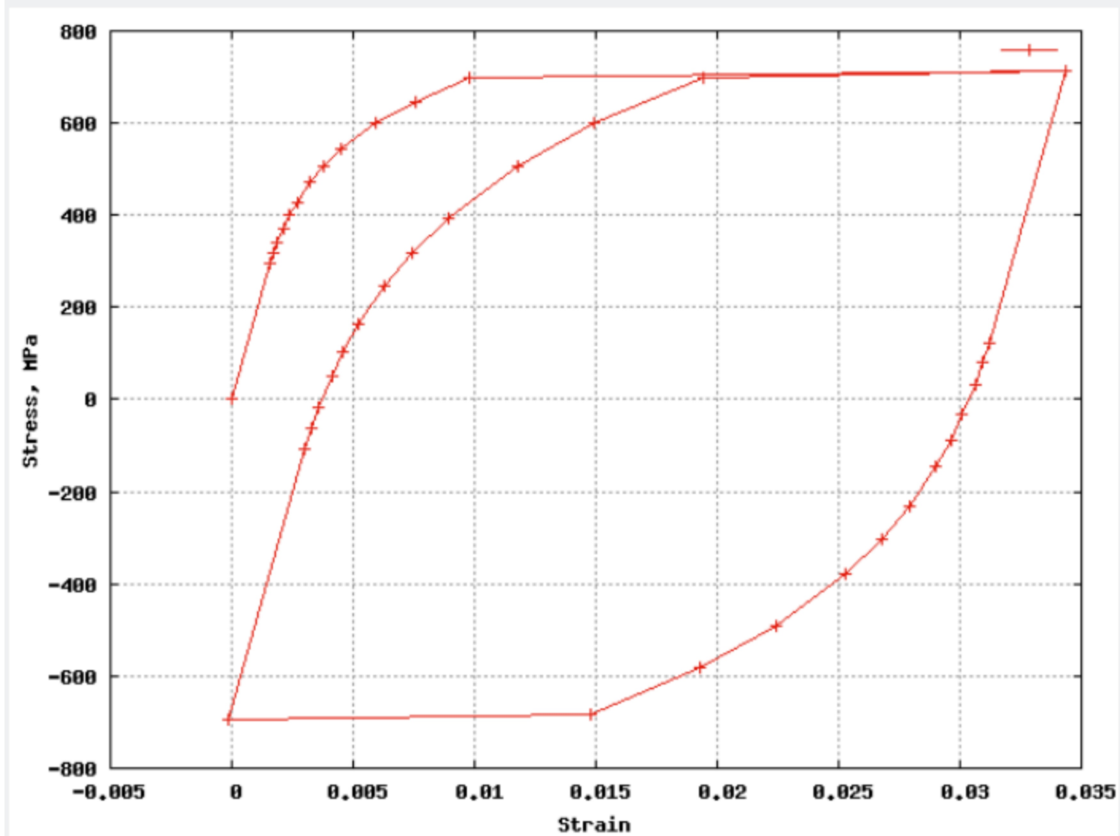
Strain limits of 0 and 0.018 were reported in Ref.[1] for the large cycles. As with the small amplitude tests one would expect that a 0.018 nominal strain would cause very large local strains at the notch roots, and that the gauge length of the specimen would be in a fully plastic state at maximum strain. Again the fully plastic state would imply that a Neuber plasticity correction, which expects an elastic field around the local plastified zone, would not be suitable for simulation.

The constant amplitude life of these notched specimens was reported however. Thus given a life one can back calculate the expected hot-spot strains that caused the fatigue.

Life Predictions (history repetitions):

```
#xcalc3  StrainLife_Reps SWaT_Life_Reps StressLife_Reps    Morrow_Reps    Goodman_Reps (Reps= Repetion
#xcalc3        103.3           101.6          103.3            55.3            33.9
```

Local Stress and Strain Response:



A loop, mostly in tension strain, shown here may have a mean stress, but due to cyclic mean stress relaxation (fde2019RelaxPres4Web.pdf (11Mb)) would have zero mean stress after one or two cycles.

In order to initiate a crack at a hot-spot at Nf=~100 one needs a strain amplitude of about 0.0175

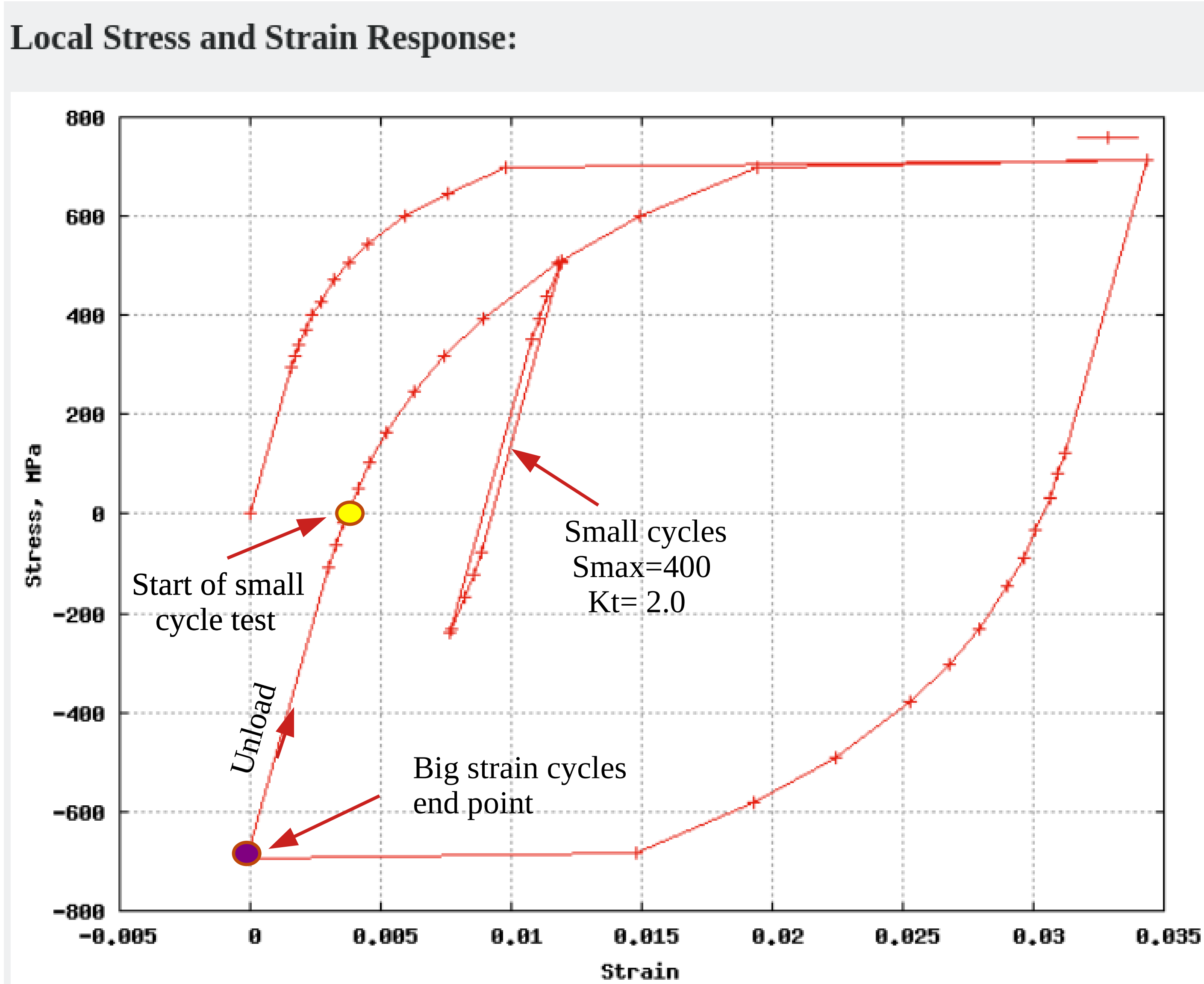
This is well beyond the available VAN80 strain test data.

High-Low Test Simulations

A local hot-spot hysteresis loop that would predict life similar to the notched specimen test lives of Nf=85 and 109 is shown in the figure below. The small cycle hysteresis loop of a Hi-Lo test has been added in the figure.

The applied strain gage strain history was a zero to max to zero type. The typical expected end of such a sequence is shown as a ● This would be followed by unloading the specimen to zero. ●

In the high-low test a switch would then be made to the application of the small cycles with Smax of either 300 or 400 mpa and Smin of zero.



Kt=1.6 Simulation Predictions of small cycle Constant Amplitude notched specimen tests.

r	Kt	Smax	Smin	Test	Simul.	Simul. Prediction
mm		mpa	mpa	Nf	$\Delta\epsilon p/2$	Nf
0.25	1.6	400	0	75,217	.0	53,747
0.25	1.6	300	0	341,000	.0	415,302
0.50	1.6	400	0	35,642	.0	53,747
0.50	1.6	300	0	182,500	.0	415,302

Life predictions are approximately a factor of 2 of test lives.

Given the Linear Damage Equation for the Hi-Lo tests of

$$n1/N1 + n2/N2 = 1$$

where N1= 103

N2= table above Simul. Nf

n1 from Hi-Lo test (See slides 12-15)

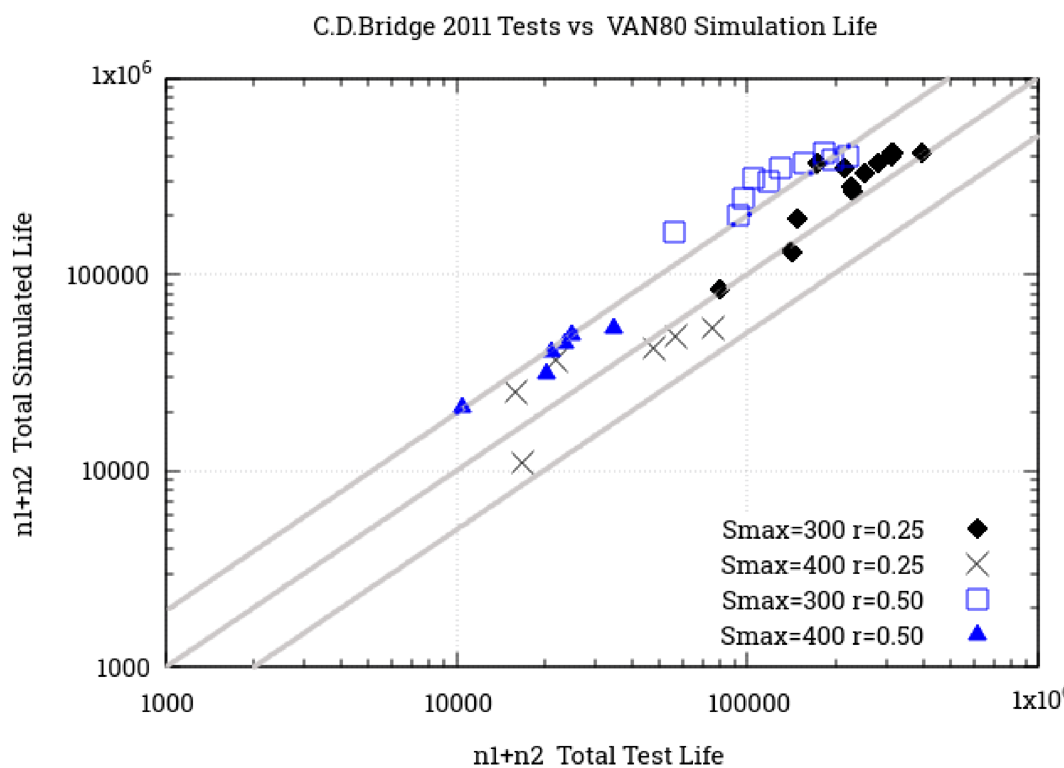
we can compute the expected n2 for the simulations.

A comparison of the simulation predicted lives with the test lives of the Hi-Lo sequence tests is shown in the figure below. The simulations assumed a Kt = 1.6 and a predicted N1f of 103 cycles, N2f of 53747 for Smax=400 and N2f=415302 for Smax=300.

The Palmgren-Miner linear damage summation was used for total fatigue life computation.

The figure indicates a difference for the r=0.25 and r=0.5mm notched predictions. Improved results could perhaps be achieved by modelling the fully plastic distortion of the samples with nonlinear FEA for a better estimate of actual Kt and hot-spot stress and strain.

Note also that these simulation predictions were done based on a single VAN-80 fatigue data set. Given more data sets a scatter profile such as shown in Ref.[6] with a lower boundary should be used to calculate design lives when required.



Summary

1. The material used in Ref. [1] appears to be similar to HSLA 550 (HSLA 980X old SAE designation, and an available VAN-80 steel.)

2. The un-notched constant amplitude test results fall on the strain-life and Neuber Stress plots of the existing VAN-80 fatigue data sets when one applies a local stress-strain fatigue hot-spot analysis.

3. A linear damage estimation for the Hi-Lo tests, using **only the test data**, seems to work reasonably well.

4. Notched specimens are expected to have fully plastic net sections which would invalidate the use of a Neuber Plasticity Correction analysis. One would expect the original circular notch shapes to be reformed. Application of nonlinear FEA to model the reformed shapes might help determine the local hot-spot stresses and strains.
   One would not expect or allow fully plastic conditions in most engineering structures and not in coiled tubing.

5. With the assumption of a rough estimate of the reformed Kt=1.6 life predictions were performed and the results correlated reasonably well with the test values; approximately within a factor of two or three which is similar to batch to batch scatter observed in fatigue stress-strain-life curves.

References:

1. C.D. Bridge, “Combining Elastic and Plastic Fatigue Damage in Coiled Tubing,” Soc. Petro. Engr. SPE 142427, Presented at the SPE/ICoTA Coiled Tubing and Well Intervention Conf. The Woodlands, Texas, USA, 5–6 April 2011.

2. W.D. Pilkey, “Peterson’s Stress Concentration Factors,” 2nd Ed. John Wiley & Sons, ISBN 0-471-53849-3 1997

3. P. Watson, T.H.Topper, “An Evaluation of the Fatigue Performance of Automotive Steels,” SAE Paper 710597, Montreal Candad, Jun. 7-11 1971.

4. F.A. Conle, “Plasticity Corrections for Elastic Analysis Results: Neuber Method” https://fde.uwaterloo.ca/Fde/Notches.new/neuber.html

5. C.D. Bridge, communication, Oct. 2020.

6. F.A. Conle, "Accounting for Scatter in Strain-Life Fatigue Testing," SAE Paper 2002-01-1279