Predicting Total Fatigue Life
(Crack Initiation and Crack Propagation)

Presented to the SAE FD&E Committee
at Minneapolis, MN on 22 October 2013
(Prepared by Semyon Mikheevskiy and Tom Cordes)
Total Fatigue Life: Crack Initiation and Crack Propagation

1. Overview of Effort

2. Residual Stress Distribution Concerns/Questions

3. Crack Initiation and Crack Propagation Analysis Background?
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

1) Real World Engineering Problems

- Geometry?
- Loading ???
- Mat’l Prop??

- Stress/Strain Analysis
- Fatigue Damage
- Unknown Fatigue Life

2) SAE FD&E “T-Bar” Test/Analysis Effort

- Geometry!
- Loading!!
- Mat’l Prop!

- Stress/Strain Analysis??
- Fatigue Damage??
- Known Fatigue Life From Fatigue Tests

Legend

- High Confidence Inputs/Analysis!!
- Lower Confidence Inputs??
- Define Improved Practice??

This effort is using “very well defined/controlled analysis inputs” to address an engineering problem to validate (or not) a potential “Total Fatigue Life Prediction Improved Practice”
Total Fatigue Life: Crack Initiation and Crack Propagation Analysis

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

Purchased “Enough” 4 A36 20ft HR bars

Microstructure, Chemistry & Hardness Sample
Total Fatigue Life: Crack Initiation and Crack Propagation Analysis

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

Play Three Video’s:
Total Fatigue Life: Crack Initiation and Crack Propagation Analysis

Steel Microstructure, Hardness, Grain Size and Chemistry

- Longitudinal Section

- Hardness: 79 HRB

- Grain size: 6
Steel Crack Initiation Strain-Life and Cyclic Stress-Strain Curves and “Fit” Analysis Constants

<table>
<thead>
<tr>
<th>E</th>
<th>Sys</th>
<th>K'</th>
<th>n'</th>
<th>s'f'</th>
<th>e'f'</th>
<th>b</th>
<th>c</th>
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<tbody>
<tr>
<td>190786</td>
<td>324.12</td>
<td>991.4</td>
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<td>1025.9</td>
<td>0.7627</td>
<td>-0.1132</td>
<td>-0.5837</td>
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</table>
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.
Total Fatigue Life: Crack Initiation and Crack Propagation Analysis

Welded Specimen Constant Amplitude Fatigue Test Results

With time histories and videos of all tests

<table>
<thead>
<tr>
<th>Max Load kN</th>
<th>R Ratio</th>
<th>Test Cycle</th>
<th>Test Counter Cycles</th>
<th>Weld Sample: Run-Position</th>
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<tbody>
<tr>
<td>24</td>
<td>0.1</td>
<td>Constant Amplitude</td>
<td>36,895</td>
<td>Hand Weld</td>
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<tr>
<td>24</td>
<td>0.1</td>
<td>Constant Amplitude</td>
<td>48,160</td>
<td>2-2</td>
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<tr>
<td>24</td>
<td>0.1</td>
<td>Constant Amplitude</td>
<td>62,047</td>
<td>6-3</td>
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<tr>
<td>24</td>
<td>0.3</td>
<td>Constant Amplitude</td>
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<tr>
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<td>262,628</td>
<td>4-3</td>
</tr>
<tr>
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<tr>
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<td>503,441</td>
<td>5-?</td>
</tr>
<tr>
<td>20</td>
<td>0.5</td>
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<td>529,250</td>
<td>4-4?</td>
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<tr>
<td>17</td>
<td>0.5</td>
<td>Constant Amplitude</td>
<td>4,900,000 NC*</td>
<td>5-1</td>
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<tr>
<td>14</td>
<td>0.1</td>
<td>Constant Amplitude</td>
<td>325,579</td>
<td>5-3</td>
</tr>
<tr>
<td>14</td>
<td>0.1</td>
<td>Constant Amplitude</td>
<td>375,813</td>
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<tr>
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<td>0.3</td>
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<tr>
<td>24</td>
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<td>Block Loading</td>
<td>138,421</td>
<td>4-1</td>
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</tbody>
</table>

*Note (NC): No crack growth found visually or by magnaflow
Total Fatigue Life: Crack Initiation and Crack Propagation Analysis

Welded Specimen Constant Amplitude Fatigue Test Results

Load (kN) vs. Cycles (N) for different R values (R=0.1, R=0.3, R=0.5).
Total Fatigue Life: Crack Initiation and Crack Propagation Analysis

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

[Graph showing bending stress distribution through the thickness at the critical location]
Total Fatigue Life: Crack Initiation and Crack Propagation Analysis

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

Weld Toe Residual Stress Distribution

Residual Stress (MPa) vs. Depth Into The Thickness/Thickness (d/t)

- Residual Stress Measured Data Before Specimen Loading
- Residual Stress "Envelope" Used in Analysis
Total Fatigue Life: Crack Initiation + Crack Propagation

Analysis #1

Tom Cordes
Fatigue Test and Analysis Engineer at HBM-nCode
After failing at retirement from John Deere (at JD for 24 years)
Crack Propagation Analysis Inputs – Define Low Cycle Fatigue “Nucleated” Crack Size and Shape

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

Initiated crack depth into the material assumed to be approximately three 0.049mm grain diameters = 0.147mm

2c (avg. defect surface length) = 6mm, c = 3mm, (ai/ci) = 0.049mm

Note: 1) The Universal Weight Function (UWF) Stress intensity Functions (SIF’s) account for the different non-linear stress distributions in the weld toe radiiuses. Some “library” solutions do not

FEM stress/strain magnitude used to calculate the crack initiation life to a crack size of ai
Total Fatigue Life – Combining the Crack Initiation + Crack Propagation Analysis

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Total Fatigue Life: Crack Initiation + Crack Propagation Analysis

CI with CPai = 3 x ro*, CPbi = 20* x ro*
Constant Amplitude Fatigue Results
Observations:
1) The crack does not nucleate as a full width edge crack.
2) There appear to be multiple cracks “linking up or merging”
3) The crack aspect ratio changes continuously as the crack propagates through the thickness

DISCRIMINATING TEST:
The analysis correlates well with the data but does not agree with physical observations of the fracture surface. The analysis life is all crack initiation.
Total Fatigue Life – Crack Propagation Analysis Includes Crack Initiation Analysis

Analysis #2

Semyon Mikheevskiy
Mechanical Engineer at SaFFD
University of Waterloo: Research Associate/Postdoctoral Fellow/Research Teaching Assistant
Total Fatigue Life – Crack Propagation Analysis Includes Crack Initiation Analysis
Experimental Strain-Life data was provided by JD

FCG constants (C, gamma) were found on previous slide

Set initial semi-circular crack with $a=b=\rho^*$ in 8mm smooth specimen

Run total life approach for each stress level and obtain the fatigue life

Good correlation with experimental data

Shows the ability of Total Life Approach to predict M-C curve using FCG data
Basics Assumptions

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

\[
\frac{da}{dN} = \frac{\rho^*}{N^*}
\]
Total Fatigue Life – Crack Propagation Analysis Includes Crack Initiation Analysis

Added a Cycle by Cycle Crack Residual Stress Distribution Tracking Capability (CRSDT)
(Calculate, From the Material’s Cyclic Stress Strain Curve, the Residual Stress Field of the Crack Tip as it Proceeds through the Time History)

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

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

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

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

- Elastic stresses ahead of the notch/crack should be redistributed due to the plastic deformations other $X_p$ distance
- Original correction $C_p$ was based on the equivalent stress
- The main idea: the classical plastic zone should be extended by the amount $D X_p$ 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
A36 Material Properties

<table>
<thead>
<tr>
<th>E</th>
<th>v</th>
<th>n'</th>
<th>K'</th>
<th>Sys</th>
<th>p</th>
<th>rho*</th>
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<td>991.4</td>
<td>324.119</td>
<td>0.152471</td>
<td>7.27E-05</td>
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- FCG rates were measured for 5 different load ratios
- Data for R=0.4 and R=0.5 (black circles) looks suspicious since FCG rates are smaller than for R=0.3
- Only R=0.1, R=0.2, and R=0.3 data will be used in the analysis
A36 FCG data in terms of Total Driving Force

<table>
<thead>
<tr>
<th>C1</th>
<th>Gamma1</th>
<th>COV1</th>
<th>C2</th>
<th>Gamma2</th>
<th>COV2</th>
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<tr>
<td>1.39E-18</td>
<td>8.733292</td>
<td>0.05681</td>
<td>3.38E-13</td>
<td>3.97455</td>
<td>0.046464</td>
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</table>

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

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

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Total Fatigue Life – Crack Propagation Analysis Includes Crack Initiation Analysis

Validation for CA loading (Welded specimen)

- Applied Stress for 1kN load

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Residual Stress Field

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

• Modified residual stress field with smooth ends and in equilibrium
FCG analysis using Total Life and RS as measured

- Total life approach was run with initial semi-circular crack with $a=b=\rho^*$ until failure
- $R=0.1$, $R=0.3$, and $R=0.5$ were used
- $L=24\text{kN}$, $L=20\text{kN}$, and $L=14\text{kN}$ were used
- OK life estimation for $R=0.1$ and $R=0.5$, less than twice of for $R=0.3$
FCG analysis using Total Life and RS modified

- Total life approach was run with initial semi-circular crack with \( a=b=\rho^* \) 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
FCG analysis using Total Life no RS

- Good predictions for $L=24kN$ which shows little importance of RS if applied load is very high. High loads produce enough stresses to make RS less important.
- Bad predictions if applied load is not that high. Life is approximately 5 times longer than experimental.

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Validation for Block loading (Welded specimen)

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

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

DISCRIMINATING TEST:
The analysis correlates well with the data and agrees with physical observations of the fracture surface. The analysis life is all crack propagation.
Redo Tom’s Crack Initiation + Crack Propagation Analysis With Semyon’s Analysis Inputs

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

April 1, 2014
Total Fatigue Life: Crack Initiation and Crack Propagation Analysis

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

Validation for Block loading (Welded specimen)

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

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

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

April 1, 2014

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