Fatigue and Fracture

Fatigue, How and Why
Physics of Fatigue

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Fatigue, How and Why

- Physics of Fatigue
- Material Properties
- Similitude
- Fatigue Calculator
Size Scale for Studying Fatigue

Atoms | Dislocations | Crystals | Specimens | Structures

10^{-10} | 10^{-8} | 10^{-6} | 10^{-4} | 10^{-2} | 10^0 | 10^2

Understand the physics on this scale

Model the physics on this scale

Use the models on this scale
The Fatigue Process

- Crack nucleation
- Small crack growth in an elastic-plastic stress field
- Macroscopic crack growth in a nominally elastic stress field
- Final fracture
Mechanisms Crack Nucleation

Nucleation in Slip Bands inside Grain
Nucleation at Grain Boundaries
Nucleation at Inclusions
1903 - Ewing and Humfrey

Cyclic deformation leads to the development of slip bands and fatigue cracks

Crack Nucleation
Slip Band in Copper

Slip Band Formation

Loading

Unloading

Extrusion

Undeformed material

Intrusion
2124-T4 Cracking in Slip Bands

N = 60

N = 240

N = 300

N = 1200

N = 2000
Crack at Particle

Material: BS L65 Aluminum

Loading: 63 ksi, R=0 for 500,000+ cycles, followed by 68 ksi, R=0 to failure. Cracks found during 68 ksi loading.

2219-T851 Cracked Particle

Crack at Bonded Particle

Material: BS L65 Aluminum

Loading: 63 ksi, R=0 for 500,000+ cycles, followed by 68 ksi, R=0 to failure. Cracks found during 68 ksi loading.

7075-T6 Cracking at Inclusion
Crack Initiation at Inclusions

Subsurface Crack Initiation

Y. Murakami, Metal Fatigue: *Effects of Small Defects and Nonmetallic Inclusions*, 2002
Fatigue Limit and Strength Correlation

Crack Nucleation Summary

- Highly localized plastic deformation
- Surface phenomena
- Stochastic process
20-25 austenitic steel in symmetrical push-pull fatigue (20°C, $\Delta \varepsilon_p/2 = \pm 0.4\%$): short cracks on the surface and in the bulk

From Jacques Stolarz, Ecole Nationale Superieure des Mines
Presented at LCF 5 in Berlin, 2003
Stage I and Stage II

loading direction

free surface

Stage I

Stage II
Stage I crack is strongly affected by slip characteristics, microstructure dimensions, stress level, extent of near tip plasticity.
Small Cracks at Notches

Crack growth controlled by the notch plastic strains
Small Crack Growth

Inconel 718

\[ \Delta \varepsilon = 0.02 \]

\[ N_f = 936 \]

N = 160

N = 240

N = 520

N = 900
Crack Length Observations

- F-495
- H-491
- J-603
- I-471
- C-399
- G-304

Crack Length, mm

Cycles

0 2000 4000 6000 8000 10000 12000 14000

0 0.5 1 1.5 2 2.5
Crack - Microstructure Interactions

Strain-Life Data

Most of the life is spent in microcrack growth in the plastic strain dominated region.
Stage II Crack Growth

Locally, the crack grows in shear
Macroscopically it grows in tension
Plastic zone size is much larger than the material microstructure so that the microstructure does not play such an important role.
Material strength does not play a major role in fatigue crack growth
Stresses Around a Crack

Maximum Load

\( \sigma \)

\( \varepsilon \)

monotonic plastic zone
Stresses Around a Crack (continued)

Minimum Load

\[
\sigma
\]

\[
cyclic\ plastic\ zone
\]

\[
\sigma
\]

\[
\varepsilon
\]
Crack Closure

S = 0

S = 175

S = 250
Crack Opening Load

Damaging portion of loading history

Opening load

Nondamaging portion of loading history
Mode I, Mode II, and Mode III

Mode I opening

Mode II in-plane shear

Mode III out-of-plane shear
Mode I Growth
Mode II Growth

shear stress

slip bands

10 µm

crack growth direction
1045 Steel - Tension

![Graph showing Fatigue Life vs. Damage Fraction for Tension and Shear](image)

- **Shear**
- **Tension**
- **Nucleation**
- *100 μm crack*

Fatigue Life, $2N_f$ vs. Damage Fraction, $N/N_f$
1045 Steel - Torsion

![Fatigue Life, 2Nf](image)

- Damage Fraction $N/N_f$
- Fatigue Life, $2N_f$
- Tension
- Shear
- Nucleation
Fatigue is a localized process involving the nucleation and growth of cracks to failure.

Fatigue is caused by localized plastic deformation.

Most of the fatigue life is consumed growing microcracks in the finite life region.

Crack nucleation is dominate at long lives.
Fatigue, How and Why

- Physics of Fatigue
- Material Properties
- Similitude
- Fatigue Calculator
Characterization

- Stress Life Curve
  - Fatigue Limit
- Strain Life Curve
  - Cyclic Stress Strain Curve
- Crack Growth Curve
  - Threshold Stress Intensity
Bending Fatigue

Bending stress:

\[ \sigma = \frac{Mc}{I} \]
SN Curve

Monel Alloy

Stress Amplitude, MPa

Cycles to Failure

Testing time @ 30 Hz

1 hour

1 day

1 month

1 year
## Fatigue Strength

<table>
<thead>
<tr>
<th>Alloy</th>
<th>$10^5$</th>
<th>$10^6$</th>
<th>$10^7$</th>
<th>$10^8$</th>
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<tr>
<td>6061-T6</td>
<td>186</td>
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<td>117</td>
<td>104</td>
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<tr>
<td>7075-T6</td>
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<td>200</td>
<td>166</td>
<td>152</td>
<td>145</td>
</tr>
</tbody>
</table>
6061-T6 Aluminum Test Data

Sharpe et. al. Fatigue Design of Aluminum Components and Structures, 1996
The fatigue limit is usually only found in steel laboratory specimens.
Very High Cycle Fatigue of Steel

Stress Amplitude, MPa

surface failures
large inclusions

conventional
fatigue limit

internal
inclusions

Cycles

10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^10
Fatigue Damage

\[ \frac{\Delta S}{2} = S_f' (N_f)^b \]

\[ N_f = \left( \frac{\Delta S}{2 S_f'} \right)^{\frac{1}{b}} \]

Damage \( \propto \Delta S^{10} \)
Fatigue Limit Strength Correlation

Fatigue Limit Strength Correlation

The graph illustrates the correlation between fatigue limit (MPa) and hardness (Rc). Points representing various quenched and tempered steels are plotted on the graph. The data points are as follows:

- 1054: 4063, 5140
- 2340: 4068, 5150
- 4032: 4130, 5160
- 4042: 4140, 8640
- 4053: 4340, 9262

The linear trend line indicates the general relationship between these two properties.
SN Materials Data

Fatigue Life, Reversals

- 93 steels
- 17 aluminum
Strain Controlled Testing
Cyclic Hardening / Softening

(a) Fully annealed
$\Delta \varepsilon = 0.0084$
$2N_f = 8060$ reversals

(b) Partially annealed
$\Delta \varepsilon = 0.0078$
$2N_f = 4400$ reversals

(c) Cold worked
$\Delta \varepsilon = 0.0099$
$2N_f = 2000$ reversals
Stable Hysteresis Loop

Hysteresis loop

\[ \Delta \sigma \]

\[ \Delta \varepsilon_p \quad \Delta \varepsilon_e \]

\[ \Delta \varepsilon \]
During cyclic deformation, the material deforms on a path described by the cyclic stress strain curve.

\[ \frac{\Delta \varepsilon}{2} = \frac{\Delta \sigma}{2E} + \left( \frac{\Delta \sigma}{2K'} \right)^{1/n'} \]
Strain-Life Data  $\Delta \varepsilon - 2N_f$

2 Reversals, $2N_f = 1$ Cycle, $N_f$
Elastic and Plastic Strain-Life Data

![Graph showing Elastic and Plastic Strain-Life Data]

- **Strain Amplitude**
  - Plastic
  - Elastic

- **Reversals, 2N_f**
  - Logarithmic scale ranging from $10^0$ to $10^7$
Strain-Life Curve

\[ \frac{\Delta \varepsilon}{2} = \frac{\sigma'_f}{E} (2N_f)^b + \varepsilon'_f (2N_f)^c \]
Transition Fatigue Life

From Dowling, Mechanical Behavior of Materials, 1999
εN Materials Data

Fatigue Life, Reversals

Strain Amplitude

Fatigue Life, Reversals

- Red: 93 steels
- Blue: 17 aluminums
Crack Growth Testing
Stress Concentration of a Crack

\[ K_T = 1 + 2 \sqrt{\frac{a}{\rho}} \]

\[ K_T \sim 2000 \]

\[ \sigma_{\text{local}} = 2000 \sigma_{\text{applied}} \]

for a crack

\[ a \sim 10^{-3} \]

\[ \rho \sim 10^{-9} \]

Traditional material properties like tensile strength are not very useful for cracked structures
Stress Intensity Factor

$$K = \sigma \sqrt{\pi a}$$

K characterizes the magnitude of the stresses, strains, and displacements in the neighborhood of a crack tip.

Two cracks with the same K will have the same behavior.
Crack Growth Measurements

\[ \sigma \]

\[ 2a \]

\[ \frac{da}{dN} \]

\[ \sigma_2 \]

\[ \sigma_1 \]

Crack size

Cycles
Crack Growth Data

\[ \frac{da}{dN} = C \Delta K^m \]

\[ m \sim 3 \]
Threshold Region

\[ \Delta K_{TH} > \Delta \sigma \sqrt{\pi a} f \left( \frac{a}{w} \right) \]

- threshold stress intensity
- flaw shape
- flaw size
- operating stresses
Threshold Stress Intensity

From Dowling, Mechanical Behavior of Materials, 1999
Non-propagating Crack Sizes

Small cracks are frequently semielliptical surface cracks

\[ \Delta K_{TH} > \Delta \sigma 1.12 \frac{2}{\pi} \sqrt{\pi a} \]

\[ a_c = 0.63 \left( \frac{\Delta K_{TH}}{\Delta \sigma} \right)^2 \]

Smooth specimen fatigue limit \( \approx \frac{\sigma_u}{2} \)

\[ a_c = 2.52 \left( \frac{\Delta K_{TH}}{\sigma_u} \right)^2 \]
Non-propagating Crack Sizes

$$\Delta K_{TH} = 5 \text{MPa} \sqrt{m}$$
Stable Crack Growth

\[ \frac{da}{dN} = C \Delta K^m \]

Stable growth region

\[ \Delta K_{TH} \]

\[ \Delta K, \text{MPa} \sqrt{m} \]
Crack Growth Data

Ferritic-Pearlitic Steel:
\[
\frac{da}{dN} = 6.9 \times 10^{-12} (\Delta K \text{MPa} \sqrt{m})^{3.0}
\]

Martensitic Steel:
\[
\frac{da}{dN} = 1.4 \times 10^{-10} (\Delta K \text{MPa} \sqrt{m})^{2.25}
\]

Austenitic Stainless Steel:
\[
\frac{da}{dN} = 5.6 \times 10^{-12} (\Delta K \text{MPa} \sqrt{m})^{3.25}
\]

Barsom, “Fatigue Crack Propagation in Steels of Various Yield Strengths”
Aluminum Crack Growth Rate Data

Crack Growth Data

### Things Worth Remembering

<table>
<thead>
<tr>
<th>Method</th>
<th>Physics</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress-Life</td>
<td>Crack Nucleation</td>
<td>0.01 mm</td>
</tr>
<tr>
<td>Strain-Life</td>
<td>Microcrack Growth</td>
<td>0.1 - 1 mm</td>
</tr>
<tr>
<td>Crack Growth</td>
<td>Macrocrack Growth</td>
<td>&gt; 1 mm</td>
</tr>
</tbody>
</table>
Fatigue, How and Why

- Physics of Fatigue
- Material Properties
- Similitude
- Fatigue Calculator
Fatigue Analysis

Material Data

Component Geometry

Service Loading

Analysis

Fatigue Life Estimate
The Similitude Concept

Why Fatigue Modeling Works!
What is the Similitude Concept

The “Similitude Concept” allows engineers to relate the behavior of small-scale cyclic material test specimens, defined under carefully controlled conditions, to the likely performance of real structures subjected to variable amplitude fatigue loads under either simulated or actual service conditions.
Fatigue Analysis Techniques

Stress - Life
BS 7608, Eurocode 3
Strain - Life
Crack Growth
# Life Estimation

<table>
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<tr>
<td>BS 7608</td>
<td>Crack Growth</td>
<td>1 - 10 mm</td>
</tr>
<tr>
<td>Strain-Life</td>
<td>Microcrack Growth</td>
<td>0.1 - 1 mm</td>
</tr>
<tr>
<td>Crack Growth</td>
<td>Macrocrack Growth</td>
<td>&gt; 1 mm</td>
</tr>
</tbody>
</table>
The Similitude Concept states that if the instantaneous loads applied to the ‘test’ structure (wing spar, say) and the test specimen are the same, then the response in each case will also be the same and can be described by the material’s S-N curve.
Fatigue Analysis: Stress-Life

Material Data
- SN curve
- $K_a$, $K_s$, ...

Component Geometry
- $K_f$

Service Loading
- $\Delta S$, $S_m$

Analysis

Fatigue Life Estimate
**Stress-Life**

- **Major Assumptions:**
  - Most of the life is consumed nucleating cracks
  - Elastic deformation
  - Nominal stresses and material strength control fatigue life
  - Accurate determination of $K_f$ for each geometry and material
Stress-Life

Advantages:

- Changes in material and geometry can easily be evaluated
- Large empirical database for steel with standard notch shapes
Stress-Life

Limitations:

- Does not account for notch root plasticity
- Mean stress effects are often in error
- Requires empirical $K_f$ for good results
The Similitude Concept states that if the instantaneous loads applied to the ‘test’ structure (welded beam on a bulldozer, say) and the test specimen (standard fillet weld) are the same, then the response in each case will also be the same and can be described by one of the standard BS 7608 Weld Classification S-N curves.
Weld Classifications

D

E

F2

G
Fatigue Analysis: BS 7608

Material Data
- Weld SN curve

Component Geometry
- Class

Service Loading
- $\Delta S$

Analysis

Fatigue Life Estimate
BS 7608

Major Assumptions:

- Crack growth dominates fatigue life
- Complex weld geometries can be described by a standard classification
- Results independent of material and mean stress for structural steels
Advantages:
- Manufacturing effects are directly included
- Large empirical database exists
BS 7608

Limitations:

- Difficult to determine weld class for complex shapes
- No benefit for improving manufacturing process
The Similitude Concept states that if the instantaneous strains applied to the ‘test’ structure (vehicle suspension, say) and the test specimen are the same, then the response in each case will also be the same and can be described by the material’s e-N curve. Due account can also be made for stress concentrations, variable amplitude loading etc.
Fatigue Analysis: Strain-Life

Material Data
- $\varepsilon_N$ curve
- $\sigma\varepsilon$ curve

Component Geometry
- $K_f$

Service Loading
- $\Delta S$
- $S_m$

Analysis

Fatigue Life Estimate
Strain-Life

Major Assumptions:

- Local stresses and strains control fatigue behavior
- Plasticity around stress concentrations
- Accurate determination of $K_f$
Strain-Life

Advantages:
- Plasticity effects
- Mean stress effects
Strain-Life

Limitations:
- Requires empirical $K_f$
- Long life situations where surface finish and processing variables are important
Crack Growth Fatigue Modeling

The Similitude Concept states that if the stress intensity (K) at the tip of a crack in the ‘test’ structure (welded connection on an oil platform leg, say) and the test specimen are the same, then the crack growth response in each case will also be the same and can be described by the Paris relationship. Account can also be made for local chemical environment, if necessary.
Fatigue Analysis: Crack Growth

Material Data
- da/dN curve

Component Geometry
- K

Service Loading
- $\Delta S$, $S_m$

Analysis

Fatigue Life Estimate
Crack Growth

- Major Assumptions:
  - Nominal stress and crack size control fatigue life
  - Accurate determination of initial crack size
Crack Growth

- Advantage:
  - Only method to directly deal with cracks
Crack Growth

- Limitations:
  - Complex sequence effects
  - Accurate determination of initial crack size
Choose the Right Model

- Similitude
  - Failure mechanism
  - Size scale
Design Philosophy

- Safe Life
- Damage Tolerant
Choose an appropriate risk and replace critical parts after some specified interval
Damage Tolerant

- Inspect for cracks larger than $a_1$ and repair.

- Safe Operating Life

 Crack size

 Cycles

Inspection
A Boeing 777 costs $250,000,000

A new car costs $25,000

For every $1 spent inspecting and maintaining a B 777 you can spend only 0.01¢ on a car
Things Worth Remembering

- Questions to ask
  - Will a crack nucleate?
  - Will a crack grow?
  - How fast will it grow?

- Similitude
  - Failure mechanism
  - Size Scale
Fatigue, How and Why

- Physics of Fatigue
- Material Properties
- Similitude
- eFatigue
eFatigue
Some Observations

Most fatigue failures are not the result of an expert using the wrong analysis etc.
Most fatigue failures are a result of a non-expert not considering fatigue because it is too complicated, not enough data etc.
Fatigue will no longer be taught in the major research universities as they focus on new science.
Prof Yukitaka Murakami

Science in the Sunlight
Science in the Shade
Science in the Sunlight
Science in the Shade
A Common Viewpoint (controversial)

Fatigue is reasonably well understood, major problems are solved and current research is applications driven towards investigating special cases and improving the accuracy of our evaluations.

Fatigue is assessment is just like finite element analysis, buy some software and make a color plot.
Fatigue Calculators

There is a need for some fatigue analysis tools that take only a few minutes to learn so non-experts can reliably conduct a fatigue assessment.
Fatigue failures are always a consideration for any structure that is dynamically or cyclically loaded. The effective use of the appropriate fatigue technology and analysis is an essential part of assuring the fatigue resistance and durability of all mechanical components.

Most fatigue technologies and fatigue analysis software have only been used by experts with costs to match. No longer. Designed and supported by the fatigue group at the University of Illinois, the Fatigue Calculator portion of the eFatigue website contains all of the technologies and tools needed for accurate fatigue assessments with an interface that is easy for the non-expert to navigate. With a Fatigue Calculator any engineer can quickly and easily conduct a fatigue or durability analysis. There are no logins or charges needed to use the Fatigue Calculator portion of the eFatigue website.

Databases for material properties, stress concentration factors, and stress intensity factors are included with the various Fatigue Calculators. Learn by Example and a description of the methods and input parameters are provided.

Fatigue analysis methods are based on stress-life, strain-life or crack growth. Fatigue technologies are applications of the methods for specific kinds of problems or materials.

New fatigue technologies and databases are continuously being developed and added to the Fatigue Calculator and eFatigue.

What is eFatigue?

eFatigue is the full featured version of the Fatigue Calculator with the ability to store personal and corporate databases for materials and loadings. Results from any analysis, including both plots and tables are stored for later retrieval. In addition, Fatigue Analyzers for more computationally intensive problems such as directly processing finite element models and variable amplitude loadings from large data files are included in eFatigue. With an appropriate login, users also have access to proprietary analysis procedures and databases. eFatigue will be available to the general public in a few months.
Constant Amplitude Home

There are three primary methods for estimating the fatigue resistance of components and structures. Stress-Life analysis assumes that the stresses always remain elastic even at the stress concentrators. Most of the life is consumed nucleating small microcracks. This is typical for long life situations (millions of cycles) where the fatigue resistance is controlled by nominal stresses and material strength. Strain-Life is used for situations where plastic deformation occurs around the stress concentrators. An example would be in a structure that has one major load cycle every day. Both stress-life and strain-life provide an estimate of how long it will take to form a crack about 1mm long. Crack growth analysis is then used to estimate how long it will take to grow a crack to final fracture. Fatigue of welds requires special considerations because of their complex shape and loading.

This section provides analysis for simple constant amplitude loading for all of the methods. It is typically found in power transmission applications such as shafts, gears etc. It is frequently used in the early stages of design to set the overall stress levels and to select appropriate materials. Many design and testing specifications are written in terms of constant amplitude loading.

Finders are provided to obtain the necessary input information for material properties and stress concentration or stress intensity factors.

Fatigue Calculators

Stress-Life
Use this method for long life situations where the strength of the material and the nominal stress control the fatigue life.

Strain-Life
This method is used for finite fatigue lives where plasticity around stress concentrations is important.

Crack Growth
Use this method to determine how long it will take a crack to grow to a critical size.

BS 7608 Welds
Complex weld shapes and residual stresses require special fatigue considerations.
Stress Concentration Factor Finder

▸ Rectangular Bars

⚡ Rounds and Shafts

- Round Shaft with a Single Fillet
- Round Shaft with Double Fillets
- Round Shaft with Groove
- Round Bar with U-shaped Groove
- Round Bar with V-shaped Groove
- Round Shaft with Semi-Circular Keyway
- Round Shaft with a Transverse Hole
Stress Concentration Factor Finder

Round Shaft with Groove

Variables

<table>
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<tr>
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<th>Value</th>
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<tbody>
<tr>
<td>D</td>
<td>10 mm</td>
</tr>
<tr>
<td>r</td>
<td>1 mm</td>
</tr>
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</table>

Results

\[ K_f = 2.16 \]
Constant Amplitude Material Property Finder

- Stress-Life
- Strain-Life
- Crack Growth

Filter by owner:
Show All ▼ Update Filter

Aluminum 5454, Forged, Su=334.0
Technology: Constant Amplitude Strain-Life
Owner: public
Material Type: aluminum
Material Alloy: 5454
Material Process: Forged
Elastic Modulus: E = 69000 MPa
Ultimate Strength: S_u = 334 MPa
Fatigue Strength Coefficient: m_f = 554 MPa
Fatigue Strength Exponent: b = -0.089
Fatigue Ductility Coefficient: m_d = 0.31
Fatigue Ductility Exponent: c = -0.62
Cyclic Strength Coefficient: K = 373 MPa
Cyclic Strain Hardening Exponent: n = 0.047

Material Reference: SAE Paper 840120 Wong

Add Strain-Life Material
Edit This Material
Delete This Material
Material Property Estimator
Constant Amplitude Strain-Life Analysis

Although most engineering structures and components are designed such that the nominal stresses remain elastic, local stress concentrations often cause plastic strains to develop in regions around them. The strain-life method assumes that the smooth specimens tested in strain control simulate fatigue damage in local regions around the stress concentration.

Use of the strain-life analysis method is limited to situations where crack nucleation and the growth of small microcracks consumes the majority of the service life.

Enter as much data as you know. If it is not enough, you will be asked for more. Sections with a light blue background represent the minimum required data to begin calculations. Other data may become necessary as calculation proceeds. Pressing the  button provides help in the form of an equation or default information for a parameter.

Experienced user mode is off. Turn experienced user mode on for a more concise form.

Click on the button below to learn by example:

Learn By Example

Loading

Loads can be entered as either the maximum and minimum values or as the stress range and mean stress.

Stresses or strains entered may be elastic-plastic. You can use elastic finite element or other elastic calculations as input by selecting (elastic) units for stress or strain. Examples include input from elastic finite element models and strength of materials calculations such as bending beams. In this case, a plasticity correction will be made to the input stresses or strains before computing the fatigue life using Neuber’s Rule.
**Constant Amplitude Strain-Life Analysis**

### Loading

**Loading Units**

<table>
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<tr>
<th>Maximum</th>
<th>$S_{\text{max}}$ or $e_{\text{max}}$</th>
<th>mm/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>$S_{\text{min}}$ or $e_{\text{min}}$</td>
<td>mm/mm</td>
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**OR**

<table>
<thead>
<tr>
<th>Range</th>
<th>$\Delta S$ or $\Delta e$</th>
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</thead>
<tbody>
<tr>
<td>Mean</td>
<td>$S_{\text{m}}$ or $e_{\text{m}}$</td>
<td>mm/mm</td>
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### Material

**Material Property Finder**

**Material Property Estimator**

<table>
<thead>
<tr>
<th>Type</th>
<th>Value</th>
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<tbody>
<tr>
<td>Fatigue Strength Coefficient</td>
<td>$\sigma'$ =</td>
</tr>
<tr>
<td>Fatigue Strength Exponent</td>
<td>$b =$</td>
</tr>
<tr>
<td>Fatigue Ductility Coefficient</td>
<td>$e_{\text{f}} =$</td>
</tr>
<tr>
<td>Fatigue Ductility Exponent</td>
<td>$c =$</td>
</tr>
<tr>
<td>Elastic Modulus</td>
<td>$E =$</td>
</tr>
<tr>
<td>Fatigue Limit</td>
<td>$S_{\text{FL}} =$</td>
</tr>
<tr>
<td>Fatigue Limit Reversals</td>
<td>$2N_{\text{FL}} =$</td>
</tr>
<tr>
<td>Cyclic Strength Coefficient</td>
<td>$K'$ =</td>
</tr>
<tr>
<td>Cyclic Strain Hardening Exponent</td>
<td>$n'$ =</td>
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</tbody>
</table>
Calculate

Save these results in your home directory:
CAStrainLife 2010_01_25_124816
Name may only contain letters, numbers, underscores, dashes, periods and spaces.

Analysis Results

\( N_r = 58855 \) cycles

Hysteresis Loop

![Hysteresis Loop](image-url)
Variable Amplitude Strain-Life Analysis

Enter at least two points. You may paste tab and newline delimited text (such as would be copied from a spreadsheet) into a box, and it will be expanded out automatically.

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>drop 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>drop 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>drop 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>drop 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>drop 5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>drop 6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Add Row  Add Column  Validate

Save data as ascii file in your home directory.

Name may only contain letters, numbers, underscores, dashes, periods and spaces.

Load Scaling

Loading Units  mm/mm  

Channel Select  
Scale Factor  
Zero Offset  

Plot  Clear Loading
### Files > dsocie

<table>
<thead>
<tr>
<th>A</th>
<th>Name</th>
<th>Last Modified</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FEMStressLife 2009_03_07_113467</td>
<td>Sat Mar 2009 10:34:52</td>
</tr>
<tr>
<td></td>
<td>FEMStressLife 2009_03_07_113503</td>
<td>Sat Mar 2009 10:35:13</td>
</tr>
<tr>
<td></td>
<td>results.rst</td>
<td></td>
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<td></td>
<td>FEMStressLife 2009_03_07_144745</td>
<td>Sat Mar 2009 13:47:53</td>
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<td>results.rst</td>
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<tr>
<td></td>
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<td>Sat Mar 2009 13:48:15</td>
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<td></td>
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<td>Sat Mar 2009 10:21:35</td>
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<td>shaft64_results.txt</td>
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<td></td>
<td>FEMStressLifeExample_1</td>
<td>Fri Feb 2009 14:49:17</td>
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<td></td>
<td>FEMStressLife_2009_02_03_1111955</td>
<td>Tue Feb 3 2009 10:20:30</td>
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<td></td>
<td>FEMStressLife_Example</td>
<td>Wed Feb 18 2009 06:51:20</td>
</tr>
<tr>
<td></td>
<td>Project/</td>
<td>Wed Jan 6 2009 06:35:29</td>
</tr>
<tr>
<td>L</td>
<td>SAE_test.txt</td>
<td></td>
</tr>
<tr>
<td></td>
<td>VAStressLife 2009_09_18_080900</td>
<td>Fri Sep 18 2009 07:09:18</td>
</tr>
<tr>
<td></td>
<td>eFatigue current model</td>
<td></td>
</tr>
<tr>
<td></td>
<td>eFatigue current model.log</td>
<td></td>
</tr>
</tbody>
</table>

### Working With Files

**Upload a file here:**

[Browse] [Upload File]

*File and directory names may only contain letters, numbers, underscores, dashes, periods and spaces.*

**Validate that checked file is a Finite Element Model and show summary:**

[Validate Finite Element Model]

**Validate that checked file is a readable Loading File:**

[Validate Loading File]
Variable Amplitude Strain-Life Analysis

Analysis

Viewing analysis VASTrainLife Example_6 owned by darrell

Analysis Results

N = 1391

Hysteresis Loop
## Probabilistic Strain-Life Analysis

### Loading

<table>
<thead>
<tr>
<th>Loading Units</th>
<th>MPa</th>
<th>Distribution Type</th>
<th>Scale Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum</td>
<td>$S_{\text{max}}$ or $e_{\text{max}}$ =</td>
<td>MPa</td>
<td>None</td>
</tr>
<tr>
<td>Minimum</td>
<td>$S_{\text{min}}$ or $e_{\text{min}}$ =</td>
<td>MPa</td>
<td>None</td>
</tr>
<tr>
<td>OR</td>
<td>$\Delta S$ or $\Delta e$ =</td>
<td>MPa</td>
<td>None</td>
</tr>
<tr>
<td>Mean</td>
<td>$S_m$ or $e_m$ =</td>
<td>MPa</td>
<td>None</td>
</tr>
</tbody>
</table>

### Material

<table>
<thead>
<tr>
<th>Material Property Finder</th>
<th>Material Property Estimator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>steel</td>
</tr>
<tr>
<td>Fatigue Strength Coefficient</td>
<td>$\sigma'_f$ =</td>
</tr>
<tr>
<td>Fatigue Strength Exponent</td>
<td>$b$ =</td>
</tr>
<tr>
<td>Fatigue Ductility Coefficient</td>
<td>$\varepsilon'_f$ =</td>
</tr>
<tr>
<td>Fatigue Ductility Exponent</td>
<td>$c$ =</td>
</tr>
<tr>
<td>Elastic Modulus</td>
<td>$E$ =</td>
</tr>
<tr>
<td>Fatigue Limit</td>
<td>$S_{\text{FL}}$ =</td>
</tr>
</tbody>
</table>
### Fatigue, How and Why

**Probabilistic Sensitivity Analysis**

The sensitivity analysis highlights the key factors contributing to fatigue failures. The diagram illustrates the cumulative percent failures against fatigue life, with a close-up of the data points showing the trend.

#### Table: Probabilistic Sensivity Analysis

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
<th>Deterministic Sensitivity</th>
<th>Probabilistic Sensitivity</th>
<th>Mean</th>
<th>COV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loading</td>
<td>$N(0.00100 \text{ mm/mm}, 0.200)$</td>
<td>-3.55</td>
<td>0.82</td>
<td>0.00100</td>
<td>0.201</td>
</tr>
<tr>
<td>$\Delta S$ or $\Delta e$</td>
<td>$N(0.00050 \text{ mm/mm}, 0.200)$</td>
<td>-0.52</td>
<td>0.12</td>
<td>0.00050</td>
<td>0.197</td>
</tr>
<tr>
<td>$S_m$ or $e_m$</td>
<td>$N(0.00050 \text{ mm/mm}, 0.200)$</td>
<td>-0.52</td>
<td>0.12</td>
<td>0.00050</td>
<td>0.197</td>
</tr>
<tr>
<td>Material Properties</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K'$</td>
<td>1441 MPa</td>
<td>0.79</td>
<td>0.00</td>
<td>1441</td>
<td>0.000</td>
</tr>
<tr>
<td>$n'$</td>
<td>0.283</td>
<td>-1.32</td>
<td>0.00</td>
<td>0.283</td>
<td>0.000</td>
</tr>
<tr>
<td>$E$</td>
<td>206800 MPa</td>
<td>-2.32</td>
<td>0.00</td>
<td>206800</td>
<td>0.000</td>
</tr>
<tr>
<td>$b$</td>
<td>-0.118</td>
<td>-2.05</td>
<td>0.00</td>
<td>-0.118</td>
<td>0.000</td>
</tr>
<tr>
<td>$c$</td>
<td>-0.412</td>
<td>-8.87</td>
<td>0.00</td>
<td>-0.412</td>
<td>0.000</td>
</tr>
<tr>
<td>$\sigma'$</td>
<td>$L(883 \text{ MPa}, 0.100)$</td>
<td>1.56</td>
<td>0.18</td>
<td>887</td>
<td>0.099</td>
</tr>
<tr>
<td>$\varepsilon'$</td>
<td>$L(0.160, 0.200)$</td>
<td>1.99</td>
<td>0.46</td>
<td>0.163</td>
<td>0.200</td>
</tr>
<tr>
<td>Stress Concentrators</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K_f$</td>
<td>$N(3.00, 0.05)$</td>
<td>-4.65</td>
<td>0.26</td>
<td>3.00</td>
<td>0.049</td>
</tr>
</tbody>
</table>

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## Multiaxial Strain-Life Analysis

### Material

You may select a material by clicking on the Material Property Finder button or specify individual properties directly.

*Material Property Estimator will show the default properties that are computed from the input values.*

<table>
<thead>
<tr>
<th>Name</th>
<th>Estimated Values</th>
<th>Aluminum 7076-T651, Su=680.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fatigue Strength Coefficient</td>
<td>$a_f = 1231$</td>
<td><strong>aluminum</strong></td>
</tr>
<tr>
<td>Fatigue Strength Exponent</td>
<td>$b = -0.122$</td>
<td>MPA</td>
</tr>
<tr>
<td>Fatigue Ductility Coefficient</td>
<td>$\beta_f = 0.263$</td>
<td></td>
</tr>
<tr>
<td>Fatigue Ductility Exponent</td>
<td>$c = -0.806$</td>
<td></td>
</tr>
<tr>
<td>Elastic Modulus</td>
<td>$E = 70000$</td>
<td>MPA</td>
</tr>
<tr>
<td>Fatigue Limit</td>
<td>$S_{FL} = 158$ MPa</td>
<td></td>
</tr>
<tr>
<td>Fatigue Limit Reversals</td>
<td>$2N_{FL} = 2000000$</td>
<td></td>
</tr>
<tr>
<td>Cyclic Strength Coefficient</td>
<td>$K' = 852$</td>
<td>MPA</td>
</tr>
<tr>
<td>Cyclic Strain Hardening Exponent</td>
<td>$n' = 0.074$</td>
<td></td>
</tr>
</tbody>
</table>

### Shear

<table>
<thead>
<tr>
<th>Name</th>
<th>Estimated Values</th>
<th>Shear</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear Fatigue Strength Coefficient</td>
<td>$\tau_f = 711$ MPa</td>
<td><strong>711 MPa</strong></td>
</tr>
<tr>
<td>Shear Fatigue Exponent</td>
<td>$b_{\tau} = -0.122$</td>
<td>MPA</td>
</tr>
<tr>
<td>Shear Fatigue Ductility Coefficient</td>
<td>$\gamma_f = 0.46$</td>
<td>MPA</td>
</tr>
<tr>
<td>Shear Fatigue Ductility Exponent</td>
<td>$c_{\tau} = -0.806$</td>
<td>MPA</td>
</tr>
<tr>
<td>Nonproportional Hardening Coefficient</td>
<td>$\Delta N_{MP} = 0$</td>
<td>MPA</td>
</tr>
<tr>
<td>Poisson's Ratio</td>
<td>$\nu = 0.3$</td>
<td>MPA</td>
</tr>
<tr>
<td>Shear Modulus</td>
<td>$G = 2.69E+04$ MPa</td>
<td>MPA</td>
</tr>
</tbody>
</table>
Calculate

Analysis Results

\[ N_f \text{ (Fatemi-Socie)} = 1.858 \times 10^3 \]
\[ N_f \text{ (SWT)} = 2.127 \times 10^3 \]
\[ N_f \text{ (Brown-Miller)} = 1.459 \times 10^3 \]
\[ N_f \text{ (Liu Mode I)} = 2.109 \times 10^3 \]
\[ N_f \text{ (Liu Mode II)} = 2.454 \times 10^3 \]
Finite Element Models Home

There are two primary methods for estimating the fatigue resistance of components and structures from Finite Element Model results. Stress-Life analysis assumes that the stresses always remain elastic even at the stress concentrators. Most of the life is consumed nucleating small microcracks. This is typical for long life situations (millions of cycles) where the fatigue resistance is controlled by nominal stresses and material strength. Strain-Life is used for situations where plastic deformation occurs around the stress concentrations. An example would be in a structure that has one major load cycle every day. Both stress-life and strain-life provide an estimate of how long it will take to form a crack about 1mm long. We suggest that you first review the constant amplitude section if you are unfamiliar with the basic methods and terminology.

This section provides analytical tools for processing FEM data for both of the methods. Fatigue analysis from a finite element model is essentially the same as constant or variable amplitude fatigue analysis with one major difference. Multiaxial stresses must be considered in the fatigue assessment. In ductile materials, multiaxial stresses considerations are particularly important because shear stresses, not principle stresses, are responsible for the nucleation and initial growth of fatigue cracks.

Both ANSYS *.rst file format and ABAQUS *.fil formats are currently supported. Results from the fatigue analysis are summarized in a series of bar charts and also returned in a *.rst or *.fil file for plotting.

Finders are provided to obtain the necessary input information for material properties.

Fatigue Analyzers

乏力 Stress-Life
Use this method for long life situations where the strength of the material and the nominal stress control the fatigue life.

力 Strain-Life
This method is used for finite fatigue lives where plasticity around stress concentrations is important.

Finders

Material Properties
Find material properties for fatigue analysis.

Technical Background

Supported File Types
Finite Element Model Stress-Life Analysis

Finite Element Model

Upload a new model file

...or use the

File Browser

Select a validated model

Summary

Loading

Single Loading Step
Maximum Load Scale Factor
Minimum Load Scale Factor

OR
Fatigue, How and Why

Calculate

Clear Results (Keep Input) Clear Form

Viewing analysis FEMStressLife_2008_11_13_032850

Analysis Results

Nr = 1.248e+02 repeats
Failure Location = element 305
Output Log

Plots

Fatigue Lives for Nodes

% variation of 4 parameters to increase life by factor of 2
NODAL SOLUTION
STEP=1
SUB  =1
TIME=1
SX    (AVG)
RSYS=0
SMN  =5.791
SMX  =12

www.efatigue.com - LOG10(LIFE) SX=Goodman; SY=Findley;
Thermo Mechanical Analysis

Loading

You may enter the loading in a series of text boxes, paste from the clipboard or as a triangle wave.

Units for $\varepsilon_x$ mm/mm

Units for $T$ °C

Units for $\Delta t$ min

Text Boxes  Clipboard  Triangle

Enter up to ten points. You may paste tab and newline delimited text (such as would be copied from a spreadsheet) into a box, and it will be expanded out automatically. The cycle begins at $\varepsilon_x=0$ and $T=20^\circ$C.

Initial Monotonic Loading

<table>
<thead>
<tr>
<th>Point</th>
<th>$\varepsilon_x$</th>
<th>$T$</th>
<th>$\Delta t$</th>
<th>Control Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.005</td>
<td>550</td>
<td>120</td>
<td>Mechanical Strain</td>
</tr>
</tbody>
</table>

Cyclic Loading

<table>
<thead>
<tr>
<th>Point</th>
<th>$\varepsilon_x$</th>
<th>$T$</th>
<th>$\Delta t$</th>
<th>Control Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.005</td>
<td>100</td>
<td>120</td>
<td>Mechanical Strain</td>
</tr>
<tr>
<td>2</td>
<td>0.005</td>
<td>550</td>
<td>120</td>
<td>Mechanical Strain</td>
</tr>
</tbody>
</table>

Use the Plot button below to verify that the correct loading information was entered.

Plot  Clear Loading
Material

SI units (mm/\text{mm}, \text{MPa}, \text{sec} \text{ and } ^{\circ}\text{C}) are expected for all material parameters.

You may select a material by clicking on the Material Property Finder button or specify individual properties directly.

Material Property Finder

Type: steel

Stress Strain Properties

\[ \varepsilon^{\text{in}} = \begin{cases} A_0 \left( \frac{\sigma}{K_0} \right)^{\eta_1} \exp \left( \frac{-\Delta H^{\text{in}}}{RT} \right) \left( \frac{\sigma}{K_0} \right) \leq 1 \\ A_0 \exp \left( \left( \frac{\sigma}{K_0} \right)^{\eta_1} - 1 \right) \exp \left( \frac{-\Delta H^{\text{in}}}{RT} \right) \left( \frac{\sigma}{K_0} \right) \geq 1 \end{cases} \]

\[
\begin{array}{|c|c|c|c|}
\hline
\sigma & 0.0000118 \\
E_\text{T} & 210000 + 35 T + 0 T^2 \text{ MPa for } T < 435 \\
E_{\text{T}} & 318000 + 283 T + 0 T^2 \text{ MPa} \\
\eta_1 & 5.4 \\
\eta_2 & 8.3 \\
K_0 & 256 + 0 T + 0.0014 T^2 \text{ MPa for } T < 304 \\
K_0 & 568 + 0.6 T + 0 T^2 \text{ MPa} \\
A_0 & 4.0e9 \\
\Delta H^{\text{in}} & 210600 \\
\hline
\end{array}
\]

Creep Damage

\[ \frac{1}{N_f^{\text{creep}}} = \int_0^{\varepsilon^{\text{cr}}} A_{\text{cr}} \Phi^{\text{dr}} \exp \left( \frac{-\Delta H^{\text{cr}}}{RT} \right) \left( \frac{\sigma}{K} \right)^{m} d\varepsilon^{\text{cr}} \]

\[ \phi_{\varepsilon^{\text{cr}}} = \exp \left[ \frac{1}{2} \left( \frac{\dot{\varepsilon}_{\text{cr}}}{\dot{\varepsilon}_{\text{mech}}} - 1 \right)^2 \right] \]

\[
\begin{array}{|c|c|}
\hline
\varepsilon^{\text{cr}} & 0.4 \\
\Delta H^{\text{cr}} & 2.491e5 \\
A_{\text{cr}} & 1.562e14 \\
m & 11.34 \\
\eta_1 & 0.333 \\
\eta_2 & 0 \\
\hline
\end{array}
\]
**Calculate**

**Analysis Results**

\[
N_f = 368 \\
N_{f_{\text{fatigue}}} = 1203 \\
N_{f_{\text{oxidation}}} = 2276 \\
N_{f_{\text{creep}}} = 692
\]
Summary

eFatigue – Bring fatigue assessment out of the shade into the sunlight where many people can have access fatigue technology on demand.
Fatigue and Fracture