Endurica
Accelerating Reliable Design

Fatigue Life Prediction for Elastomers

www.endurica.com
About Endurica – The Company

• LLC Founded in March 2008

• Vision
  – Make fatigue life prediction of elastomers as widely practiced and well-understood as fatigue life prediction of metals.
  – Materials, component, and system developers will have capable, reliable, proven methods for assessing fatigue life.

• Mission
  – Provide services, technology, and training that accelerate reliable design for elastomer materials and components.
  – Empower practitioners with knowledge, methods, tools for fatigue analysis.

• Technology
  – We develop and apply the Endurica fatigue life prediction code - a patented, proprietary system for analyzing the effects of multiaxial, variable amplitude duty cycles on elastomers.
About Endurica – Business Model

Analysis Services

Consulting

Training

Technology Licensing
About Endurica – The Code

- **Interface**
  - text file input and output
  - DOS command line execution
- **Fatigue life prediction code for rubber**
  - Patented plane-specific algorithm
  - Stress-strain, fatigue laws applicable to rubber
- **V1.0 – 2000** – initial implementation of plane-specific algorithm
- **V1.5 – 2001** – first release for production use
- **V2.1 – 2006** – wider selection of material models, easier inter-use with ABAQUS
- **V2.17 – current release**
- **Investment to Date**
  - 3 solid man-years code development
  - 4 man-years code validation
  - 1 Patent
  - 2 PhD theses
  - Publications: 25+ (most cited on topic “rubber fatigue”, according to Google scholar)
  - Joint Industry Program with international partners in automotive OEM business
- **Current State**
  - Thousands of analyses completed: tires, mounts, lab specimens, medical devices
  - Small user base
  - Business decision - offer as a service, initially
- **Working with a small number of customers – “word of mouth”**
  - Automotive OEM, OEM supplier, medical devices, energy

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Developing a Rubber Component

Industry Sectors:
- Medical devices
- Automotive components
- Energy (Oil and Gas)
- Consumer products
- Military
- Aero

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Material Properties

Because of their macromolecular structure, elastomers exhibit unique behavior and require specialized analysis methods.

**Endurica is the first commercially available fatigue life simulation that addresses the unique characteristics of elastomeric materials.**

Given the material properties and duty cycle of a rubber component, the number of cycle repeats that will be endured before fatigue failure can be computed.

Endurica considers the factors that distinguish elastomers:

- Finite Strains
- Nonlinear Elasticity
- Strain Crystallization
- Time Dependence
- Temperature Dependence
- Ozone Attack
- Mullins Effect

Fatigue Life Prediction
Analysis Issues

**Applied to Structure**

- Load / Displacement vs. Fraction of Mission Profile

**Material Characterization**

- Crack Driving Force vs. Fraction of Mission Profile

**Multiaxial**

- Experienced by Crack

**Variable Amplitude**
Life Calculation Scheme

\[ F(t) \]

FEA

\[ \varepsilon_{ij}(t), \sigma_{ij}(t) \]

Equivalence Parameter
(Loading Conditions Experienced on a material plane)

\[ \vec{r}(\theta, \phi) \]

Energy Release Rate
(Loading Conditions Experienced on at Crack Tip)

\[ \frac{dc}{dN} = f(T, R) \]

\[ N_f(\theta, \phi) = \int_{c_0}^{c_f} \frac{1}{f(T, R)} \, dc \]

\[ \theta_{\text{min}}, \phi_{\text{min}}, N_{f,\text{min}} \]

Deals with:
• Crack closure
• Multiaxiality
• Critical plane
• Nonlinear elasticity
• FCG behaviors unique to elastomers

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US Patent No. 6,634,236 B1
Validation Experiences
Axial / Shear Fatigue Experiments


Test Specimen

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Loading Paths Investigated

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Cracking Plane Observations

Predicted Failure Plane, deg
Observed Failure Plane, deg

Path A Path B Path CPath D1
Path D2 Path E Path F Path L
Path G Path H Path I

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Multiaxial Fatigue Life Correlation

\[ N_f = 16100 \left( W_{c,max} \right)^{-2.15} \]

\[ r^2 = 0.78 \]
Variable Amplitude Test Signals

- Signals vary $R$-ratio, load severity, and load sequence in a repeated block format.
Variable Amplitude Results

Natural Rubber

SBR

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Cadwell’s Test Specimen
Cadwell’s Test Specimen

Specimen under lateral compression
Cadwell’s Test Specimen

Specimen under lateral compression and shear.
Experimental Results

- **Loading**
  - Compression / Tension
  - Cyclic Shear

- **R Ratio**
  - Fully Relaxing ($R = 0$)
  - Non-Relaxing ($R > 0$)

- **Long Fatigue Life**
  - Threshold Effects
  - Ozone attack

<table>
<thead>
<tr>
<th>SHEAR CYCLE</th>
<th>LATERAL STRAIN</th>
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<tbody>
<tr>
<td></td>
<td>NONE</td>
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<tr>
<td>-25% TO +25%</td>
<td>A</td>
</tr>
<tr>
<td>0% TO 50%</td>
<td>B</td>
</tr>
<tr>
<td>75% TO 125%</td>
<td>C</td>
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**COMPLEX!**
Finite Element Analysis

- 10 x 10 x 10 mesh
- 3-D, 2nd order, hybrid formulation, reduced integration elements (C3D20RH)
- Neo-Hookean constitutive model, $C_{10} = 0.5$ MPa
- Sinusoidal Cyclic Shear Loading
- Strain History Recovery: Element Centroids
Finite Element Analysis

<table>
<thead>
<tr>
<th>Edge View</th>
<th>Front View</th>
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<tbody>
<tr>
<td>A</td>
<td>D</td>
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<tr>
<td>C</td>
<td>F</td>
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</tbody>
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- A: Edge View
- D: Front View
- G: Edge View
- H: Front View
- I: Edge View
Crack Growth Properties

\[ T_c = 10 \times 10^3 \text{ J/m}^2 \]
\[ r_c = 5 \times 10^{-3} \text{ mm/cyc} \]
\[ F = 2 \]
\[ T_t = 450 \text{ J/m}^2 \]
\[ T_0 = 100 \text{ J/m}^2 \]
\[ r_z = 8 \times 10^{-9} \text{ mm/cyc} \]
\[ C = 7 \]

\[ F(R) = F e^{CR} \]
Results
Material Characterization
Stress-Strain Behavior

\[ W = G \sum_{i=1}^{5} \frac{C_i}{\lambda_m^{2i-2}} (\bar{I}_1^i - 3^i) \]

Arruda-Boyce potential

- Simple Uniaxial
- Pure Shear
- Equibiaxial

\[ G = 3 \text{ MPa} \]
\[ \lambda_L = 4 \]
Effect of Strain Crystallization on FCG Rate

NR Crack Growth Results

SBR Crack Growth Results

Typical Computed Haigh Diagram
Match to known behavior
Comparing Haigh Diagrams

Control

Non-Crystallizing

No Crystallization
Comparing Cadwell Diagrams
Duty cycle analysis
Multiaxial Input
Identification of Critical Plane

![Graph showing the relationship between crack orientation and Log10(Fatigue Life). The graph peaks at a specific crack orientation, indicating the critical plane.]
Crack Plane Experience

![Graph showing cracking energy density over time](image-url)
Rainflow Count Results – Peak and R ratio for each event
Damage Rate, by event

Note: Crack growth rates are evaluated at the initial flaw size

\[ r = \sum_{i=1}^{N} r_i(W_{c,\text{max}}, R) \]
Construction of Abbreviated Strain History

![Graph showing fatigue life and crack orientation with various M values and strain plots for different angles and strain levels.](image)
Endurica Distinguishers

- Addresses unique aspects of elastomers
  - Hyperelasticity / finite straining
  - Strain crystallization
  - Mullins effect
  - Time-dependence
- Advanced fatigue simulation methods
  - Critical plane
  - Rainflow
  - Crack closure
- Founded on a large body of experimental validation work
- Efficient material characterization
Our Analysis Services

- **Material Characterization**
  - We determine the parameters needed to represent your materials in our analysis process, and generate plots showing computed response over a range of conditions.

- **Fatigue Life Prediction**
  - We apply our patented analysis process to show how your materials will endure under your given duty cycles. Our specialty is accounting for the effects of multiaxial, variable amplitude strain histories, as you might determine via Finite Element Analysis or experiment. We can efficiently analyze duty cycles from every element in a finite element model to locate the point of minimum fatigue life.

- **Failure Site Analysis**
  - Our analysis can show which planes are likely to develop cracks, and how the applied strain history is transformed into the localized experience of the failure site.

- **Duty Cycle Analysis**
  - Our analysis can identify the events that contribute most to crack development. This enables developers to focus design mitigation efforts on the most critical loading conditions, test engineers to compress the duty cycle while retaining relevance to actual service conditions.