# Achieving Durability Before You Build and Break: Modern Solutions for Fatigue Analysis

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Endurica LLC

SCC Berlin 2015

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# What does it take to design a durable part?

## Physical Prototype

- Compounder
- Product Engineer
- Test Engineer
- Mold development
- Prototype production
- Multiaxial servohydraulic component testing
- 4-poster testing
- Fleet testing

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$20k-200k, 2 months-2 years per iteration!

## Virtual Prototype

- Software / computer
- Material characterization
- Analyst

__________

$500-$5000, 2 hours – 2 days per iteration

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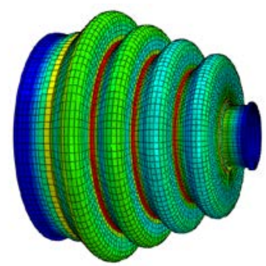
# Pre-prototype Solutions for Elastomer Durability


- Material behavior


Courtesy Axel Products

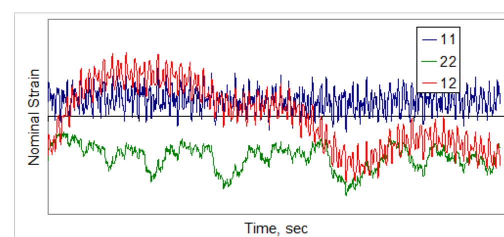
Fatigue Property Mapping
Know Your Material


- Geometry
- Service History



**fe-safe/Rubber**


- FEA
- Fatigue Analysis
- Test Development
- Design Review
- Failure Diagnosis
- Service Life Projection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# Fatigue Property Mapping

## Know Your Material

**Hyperelastic Module**
Simple, Planar, and Equibiaxial tension, Mullins Effect

**Core Fatigue Module**
Fully Relaxing Behavior from both nucleation and fracture mechanical perspectives

**Intrinsic Strength (>$10^6$ cycles) Module**
Quantify endurance limits

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Elastomer Fatigue Property Evaluation

**Endurica Project Number:** [redacted]
**Material:** [redacted]

Report Date: 6 October 2014

| Experiments Conducted by: | Analysis and Reporting Prepared by: |
| --- | --- |
| Axel Products, Inc.<br>Industrial Highway<br>Ann Arbor, Michigan | Endurica LLC<br>1219 W. Main Cross St., Ste 201<br>Findlay, Ohio 45840 |
| www.axelproducts.com | www.endurica.com |

### Executive Summary

The fatigue capabilities of a rubber compound are characterized. The characterization enables estimates to be made of fatigue life across a broad range of potential duty cycles and operating conditions. The characterization includes Endurica's core suite of experiments and analyses. Parameters for use in the Endurica fatigue life solver are included.

The Core characterization provides information pertaining to cases involving fully relaxing cycles applied at room temperature. A strain-life curve is established, along with fatigue crack growth law parameters and an estimate of the typical naturally occurring flaw size.

The Hyperelastic option provides information needed to define the stress-strain law for Finite Element Analysis. A 3rd order Ogden hyperelastic law has been selected, and its parameters determined. Parameters for describing the Mullins effect are also provided.

```
ELASTICITY_TYPE=OGDEN
MU1=6.31597e-09 !MPa
MU2=5.36219 ! MPa
MU3=0.0154611 !MPa
ALPHA1=1.59932
ALPHA2=-1.59932
ALPHA3=14.1301
MULLINSR=2.5007
MULLINSM=0.12974 ! MPa
MULLINSBETA=0.18899
BULK_MODULUS=1500 ! MPa
FATIGUE_TYPE=THOMAS
TCRITICAL=4.7861 ! kJ/m^2
RC=13.5884 ! mm/cyc
F0=3.5872
FLAWSIZE=0.0045 ! mm
FLAWCRIT=1 ! mm
TEMPREF=100.0 ! degC
TEMPCOEF=0.0 ! 1/degC
```

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roperty Evaluation

unction of the energy release rate $T$, as shown
to the collection of measurements.

(2)

hese results are summarized in Table 3.

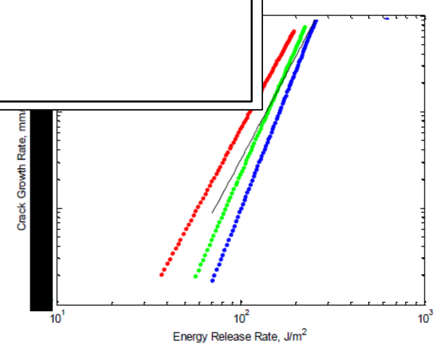


Figure 4. Fatigue crack growth curves for replicates 1-3.

Table 3. Power law fatigue crack growth parameters (mm/cyc vs. J/m$^2$).

| Material | [redacted] |
| --- | --- |
| F | [redacted] |
| B | [redacted] |

**Extended Life (>$10^6$ cycles) Module**
Quantify endurance limit, estimate aging rate of stiffness, intrinsic and ultimate strength

**Thermal Module**
Quantify dissipative properties, thermal properties, temperature dependence

**Nonrelaxing Module**
Quantify Strain Crystallization, Min and Mean Strain Effects

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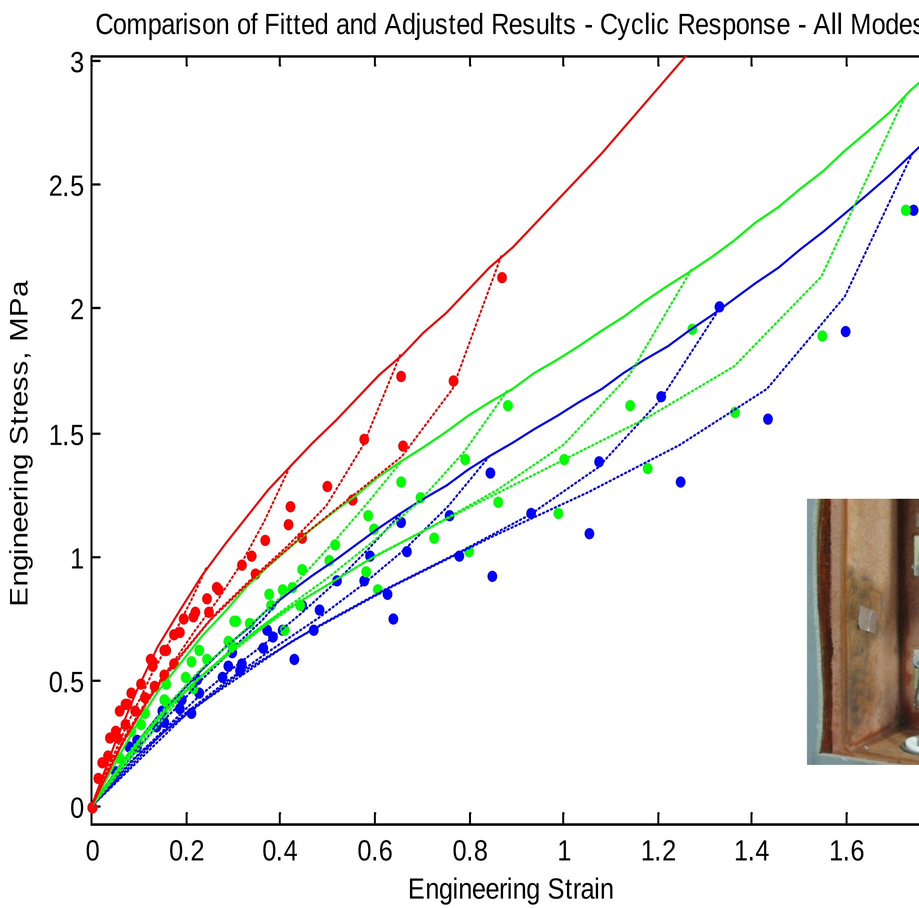
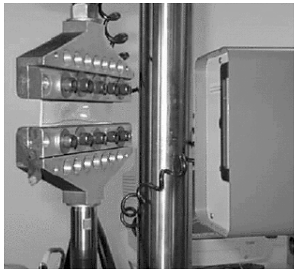
# Cyclic Stress-Strain Behavior

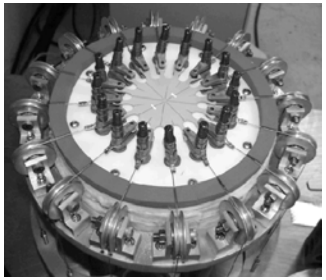
**Hyperelastic Option**
Simple, Planar, and Equibiaxial tension, Mullins Effect




$$W = \sum_{i=1}^{N} \frac{2\mu_i}{\alpha_i^2}\left(\bar{\lambda}_1^{\alpha_i} + \bar{\lambda}_2^{\alpha_i} + \bar{\lambda}_3^{\alpha_i} - 3\right)$$

$$\eta = 1 - \frac{1}{r}\operatorname{erf}\left[\frac{\tilde{W}(I_{1,\max}) - \tilde{W}(I_1)}{m + \beta \tilde{W}(I_{1,\max})}\right]$$

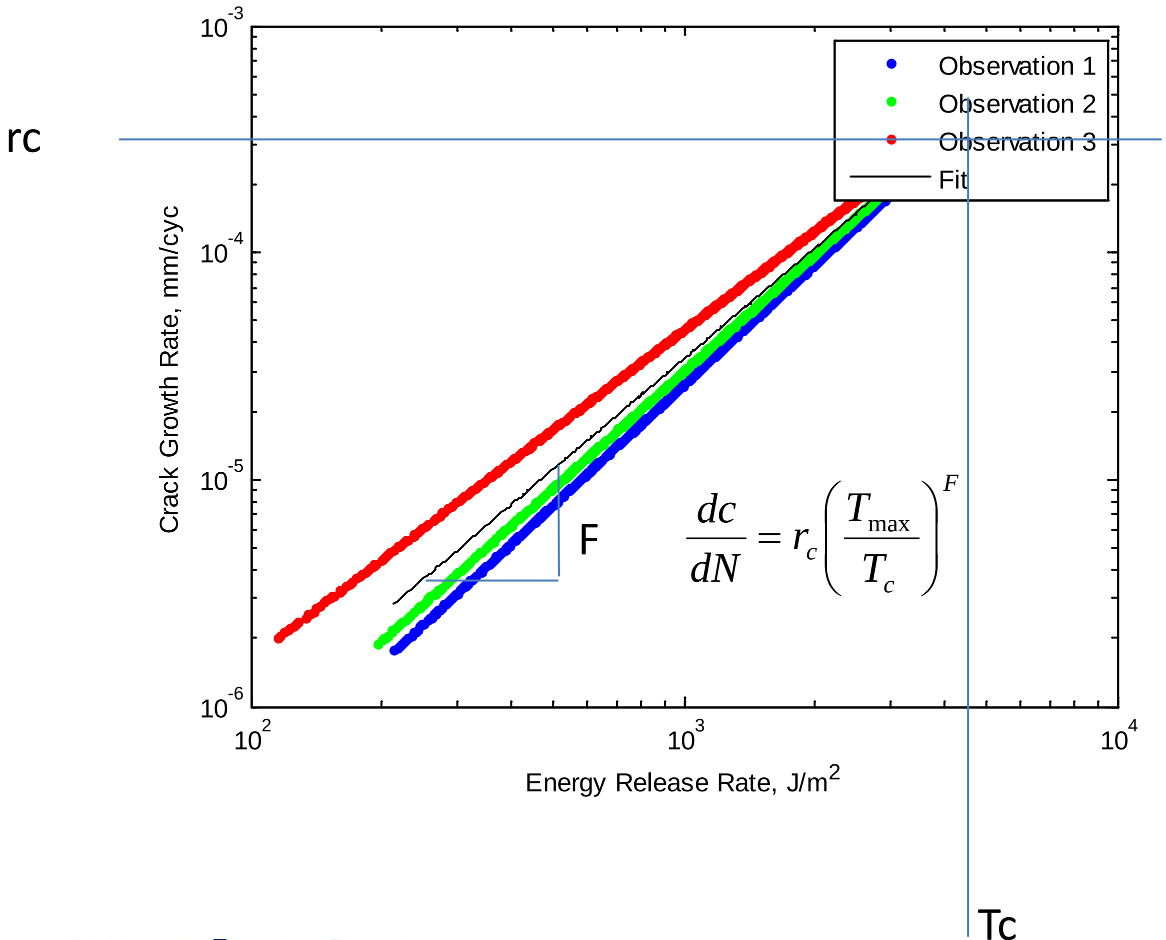




Fatigue Property Mapping
Know Your Material

**Core Fatigue Test**
Fully Relaxing Behavior from both nucleation and fracture mechanical perspectives

# Crack Growth Characteristic




Courtesy Axel Products

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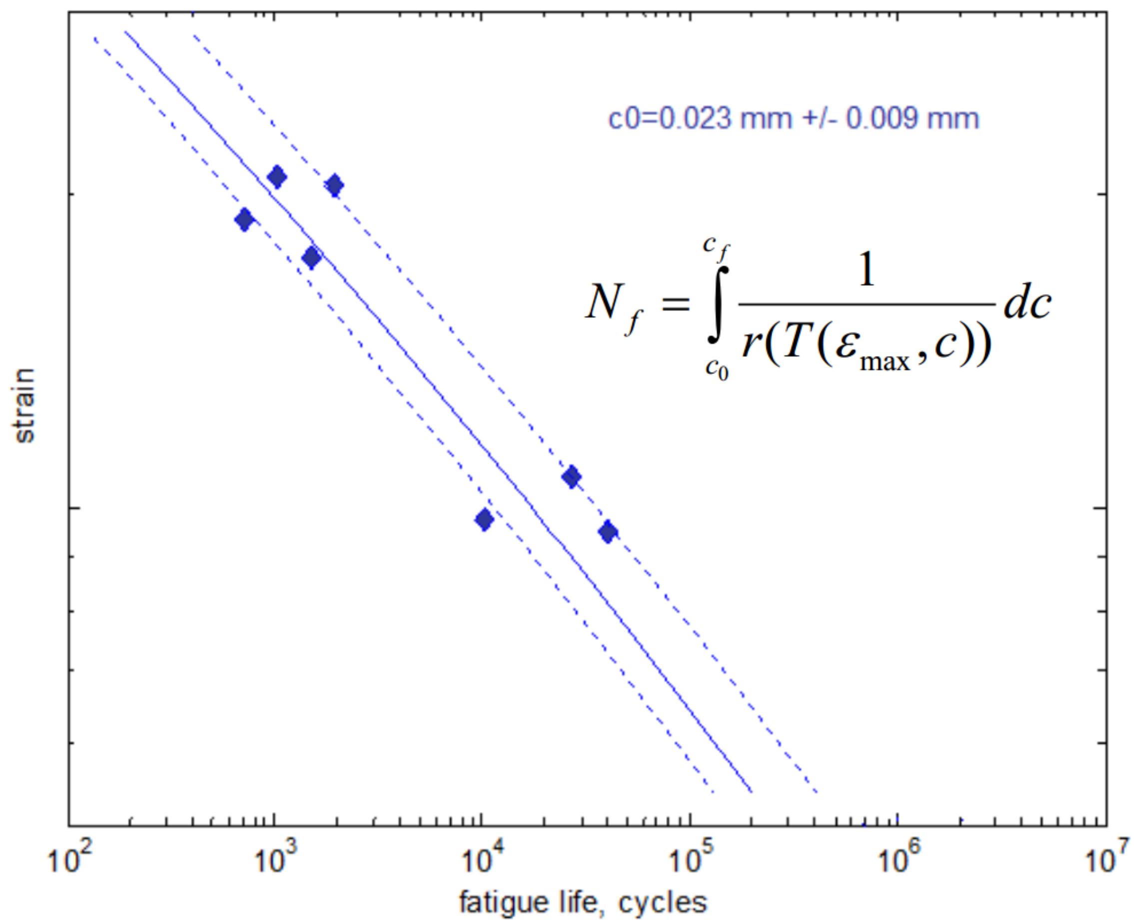
# Strain Life Curve / Crack Precursor Size



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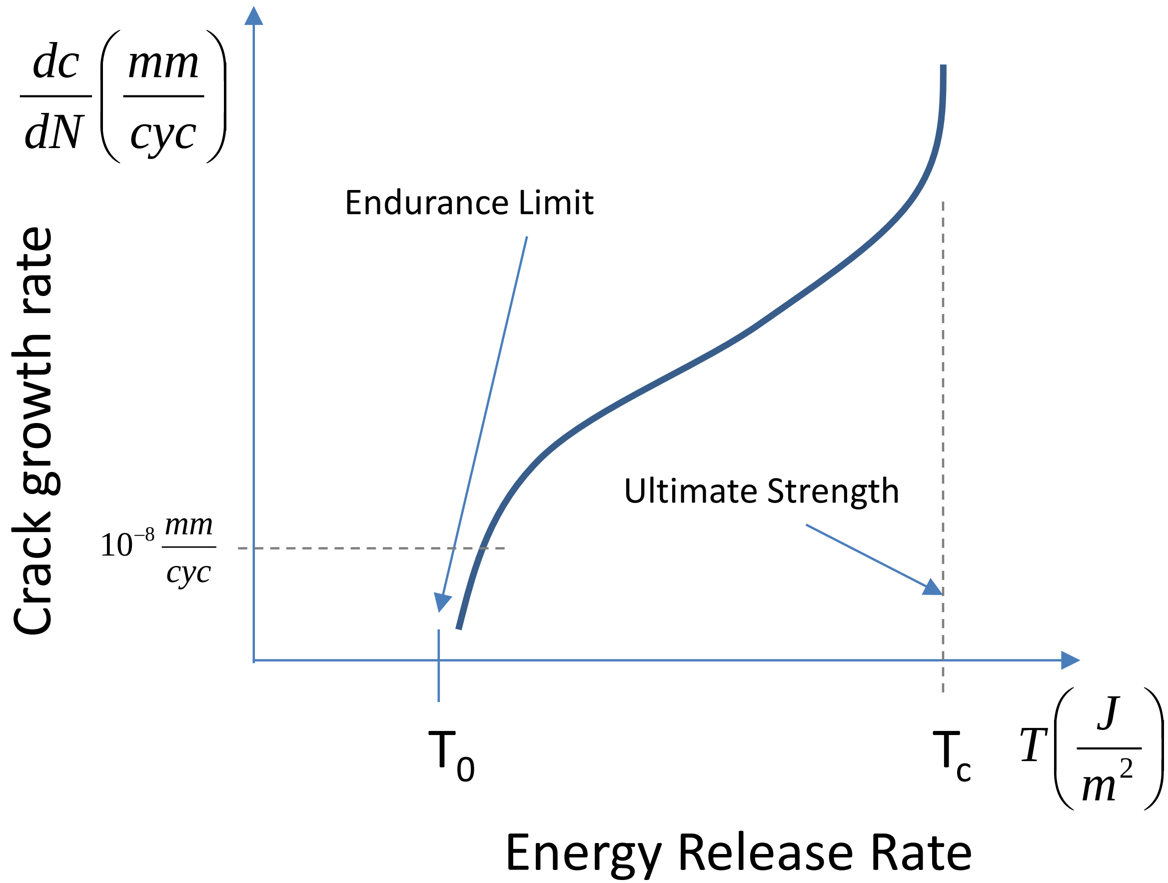
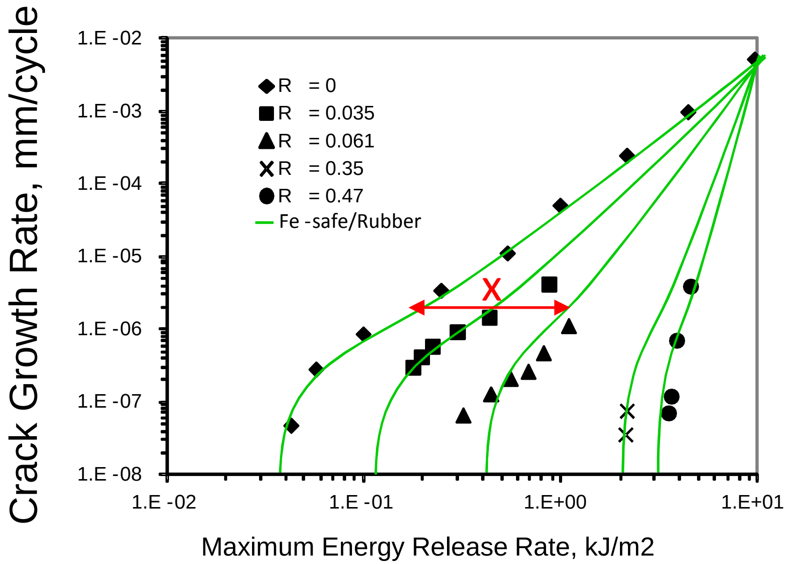
# Minimum Requirement for Crack Growth

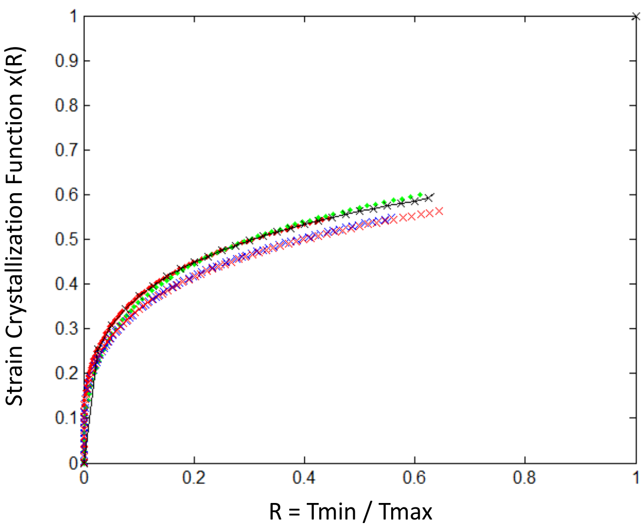
**Intrinsic Strength Option ($>10^6$ cycles)**
Quantify endurance limit



# Strain Crystallization Effects

**Nonrelaxing Option**
Quantify Strain Crystallization, Min and Mean Strain Effects

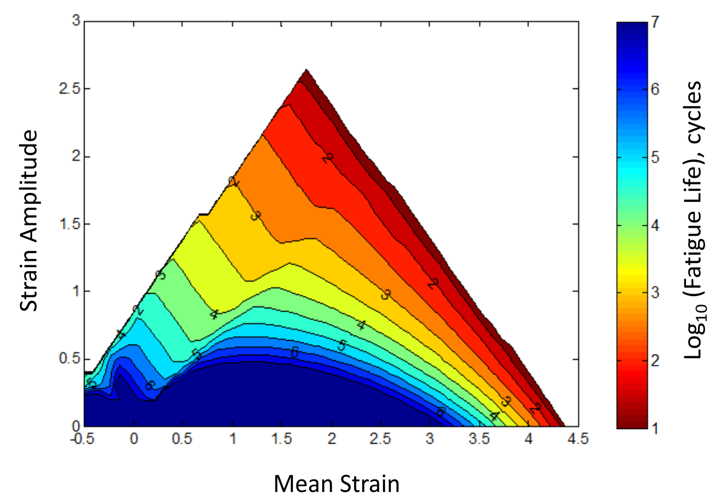


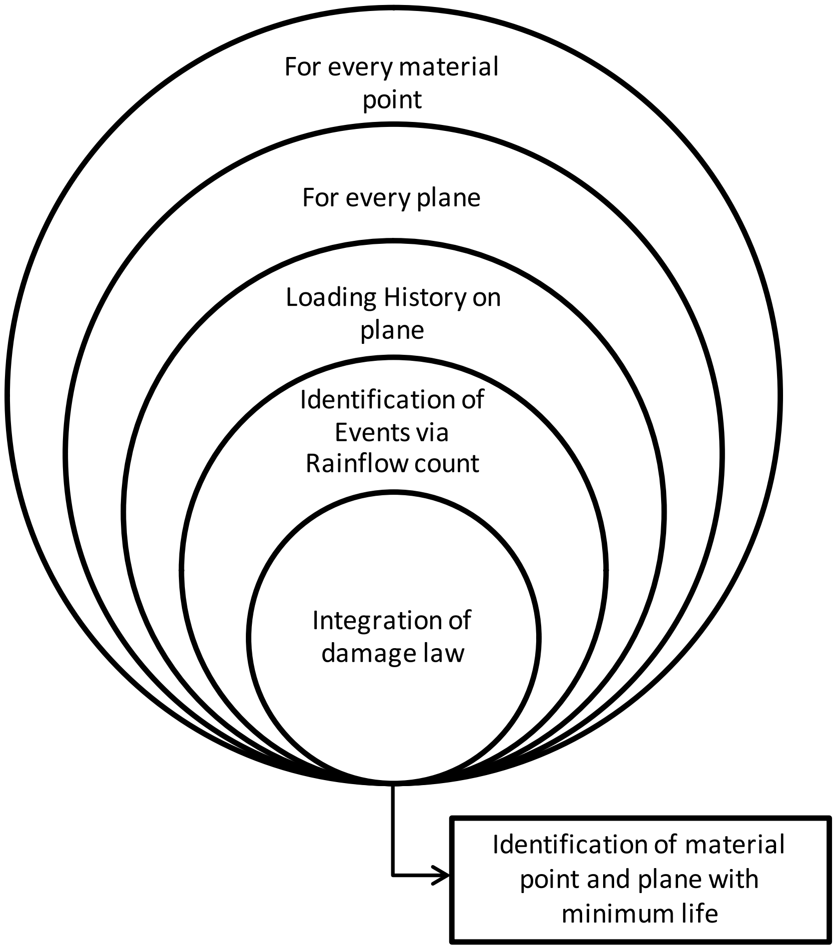
# Technology: Realistic Material Modeling

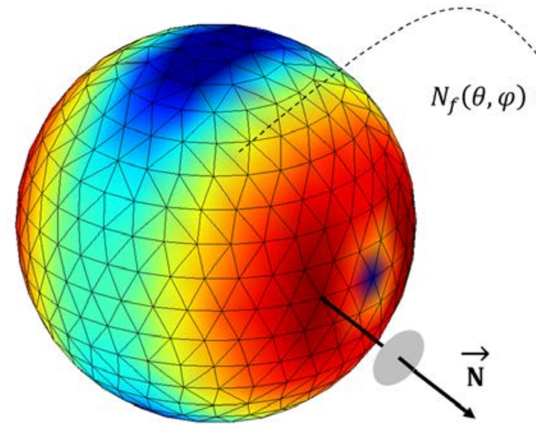
$$\frac{dc}{dN}$$

- Cyclic
  - R=0
    - Powerlaw
    - Lake-Lindley
    - Table Lookup
  - R>0
    - Paris
    - Mars-Fatemi
    - Table Lookup
- Steady
  - Ozone attack
    - Gent-McGrath
  - ViscoElastic Rupture
    - Powerlaw
    - Table Lookup



# Technology: Critical Plane Analysis

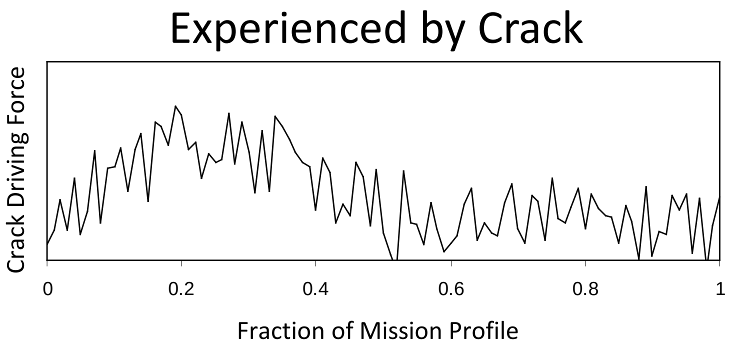



$$N_f(\theta,\varphi) = \int_{a_0}^{a_f} \frac{1}{r(T(\theta,\varphi,a))} da$$

- Continuum / nucleation viewpoint
- Accounts for finite straining
- Crack closure in compression
- Failure plane identification
- Crack precursor loading experience

# Technology: Damage accumulation




$$r = \sum_{i=1}^{M} f_i(T_{\max}, R)$$

Crack growth rate per application of given duty cycle

$$N_{\theta,\phi} = \int_{a_0}^{a_f} \frac{1}{r(T(a,t))} da$$

Number of repeats of duty cycle required to develop a crack

- Rainflow counting
- Based on numerical integration of crack growth rate law
- Arbitrary multiaxial, variable amplitude loading history
- Time-domain scheme enables direct identification of damaging events

Harbour, Ryan J., Ali Fatemi, and Will V. Mars. "Fatigue life analysis and predictions for NR and SBR under variable amplitude and multiaxial loading conditions." *International Journal of Fatigue* 30.7 (2008): 1231-1247.

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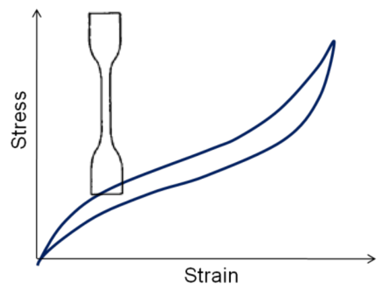
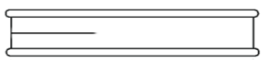
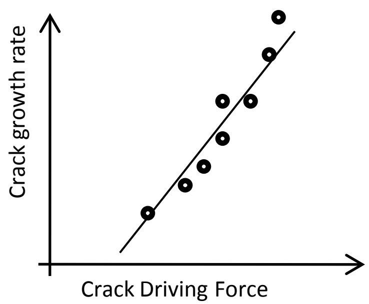
# Solution Workflow

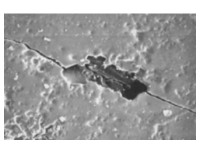
**fe-safe/Rubber**

Material Properties



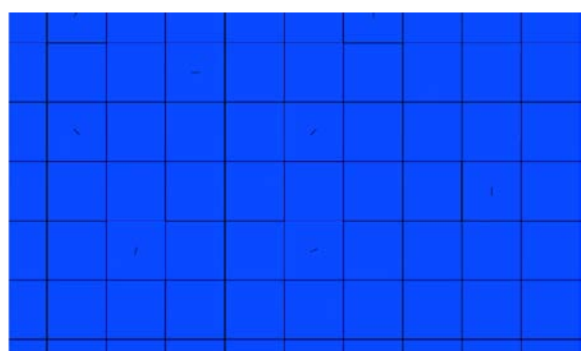


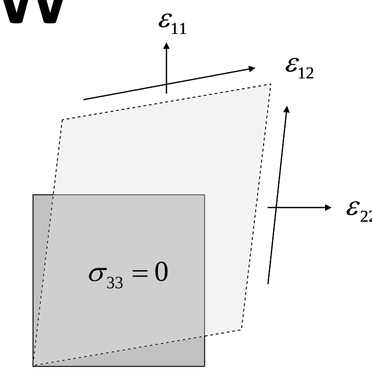



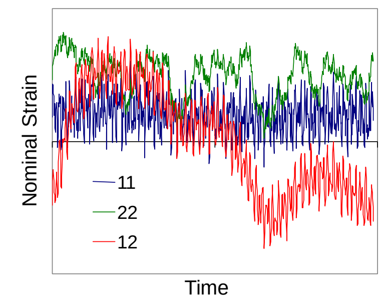
Given the material properties and strain history of a rubber component, compute the number of cycle repeats that will be endured before the fatigue process produces cracks of a given size.

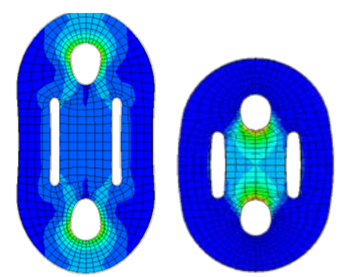
$$N_f = \int_{a_0}^{a_f} \frac{1}{r(T(W,a))} da$$

Fatigue Life Prediction





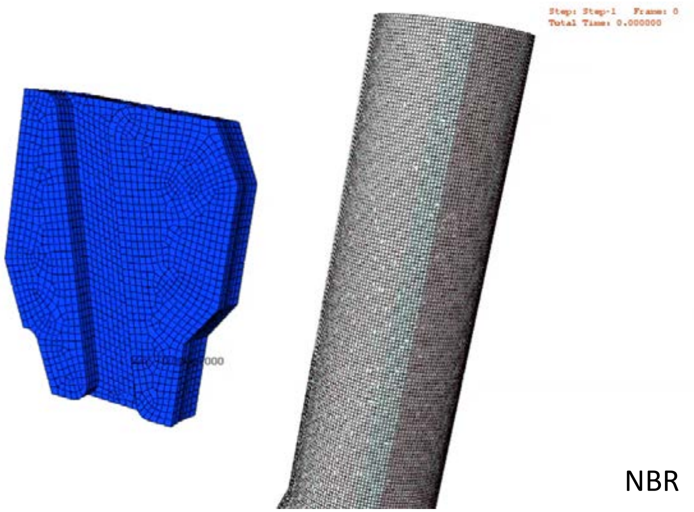



Finite Element Model

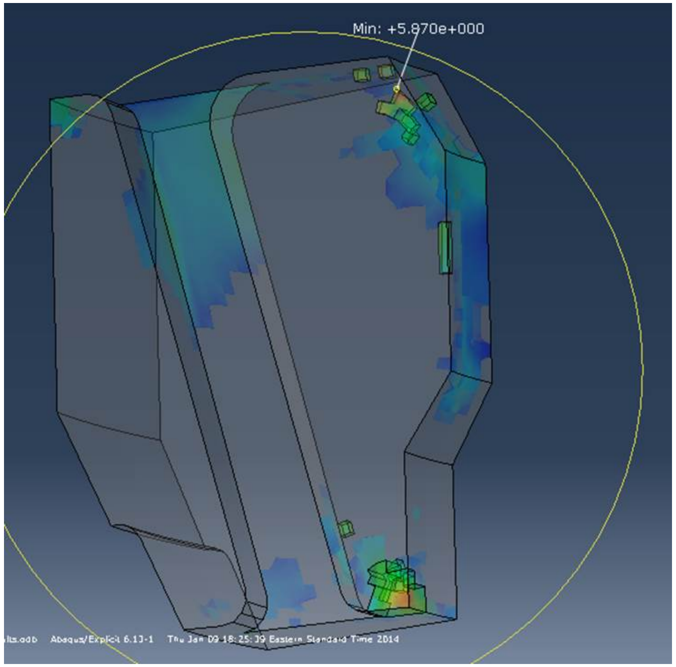
# FE Analysis of sealing element

```
*Hyperelastic, arruda-boyce
 209.6,     3.17, 6.67e-06
```



NBR

c0=0.100 mm
cf=1.00 mm
F0=2
Tc=65500 J/m2
Rc=0.01 mm/cyc
T0=100 J/m2

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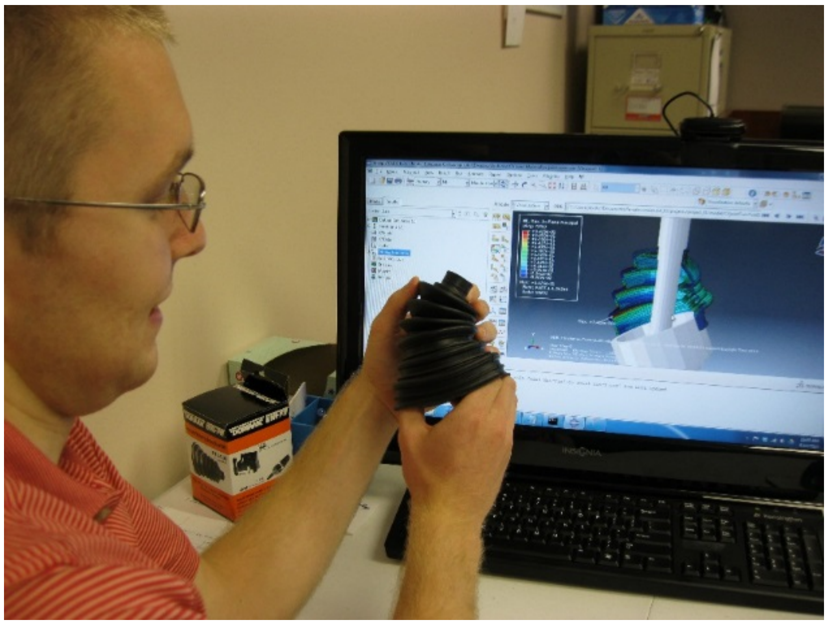
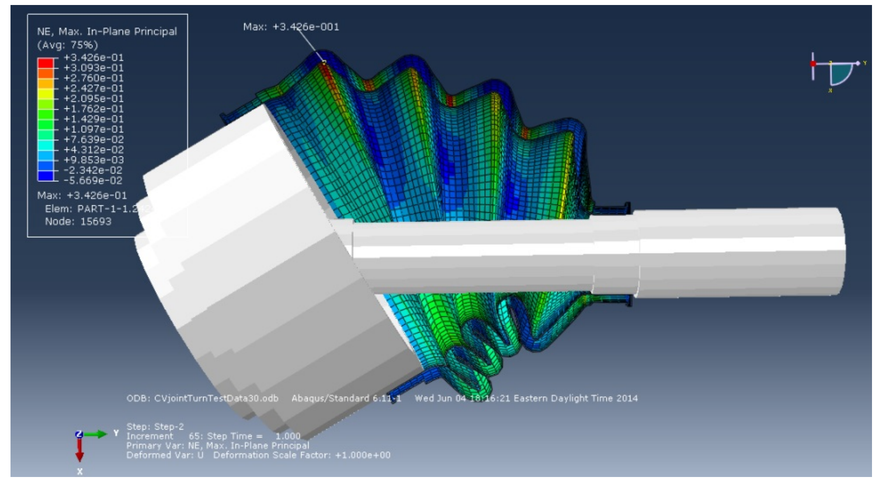
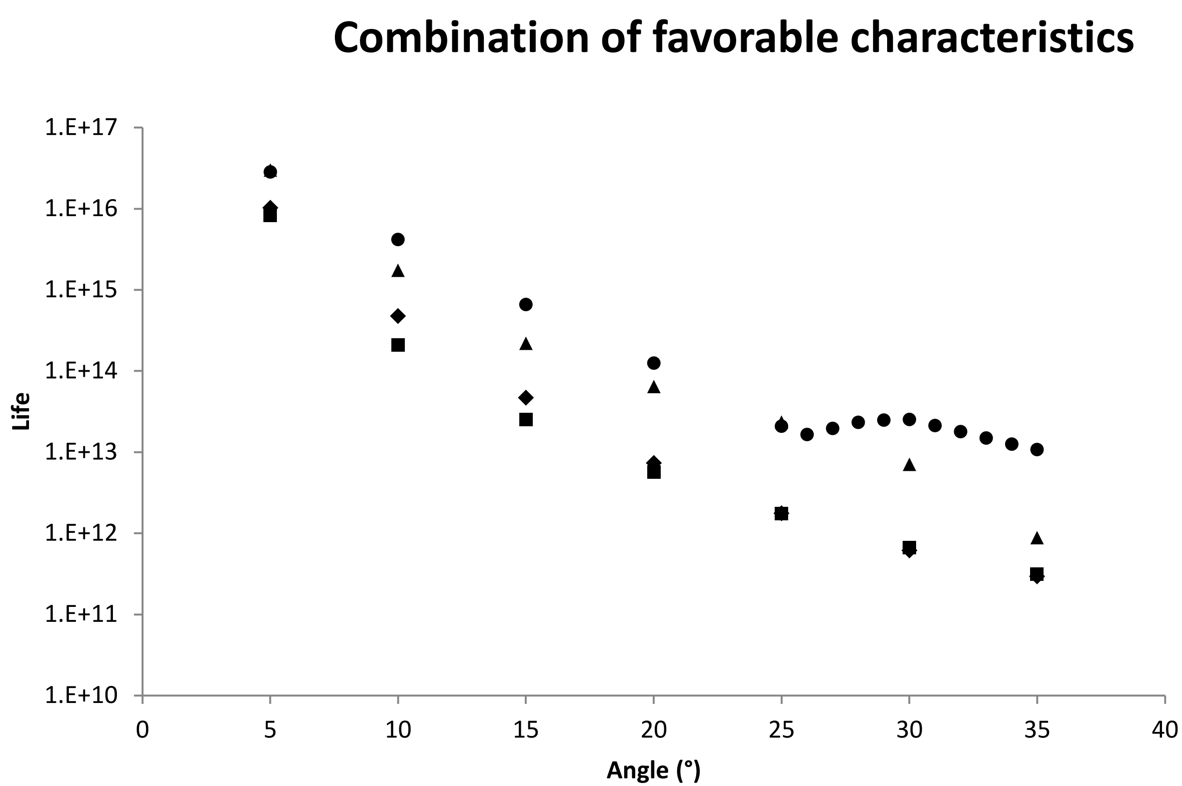
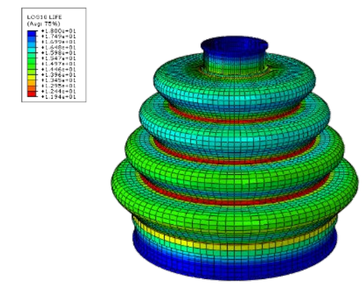
# CV Boot Fatigue Analysis Project

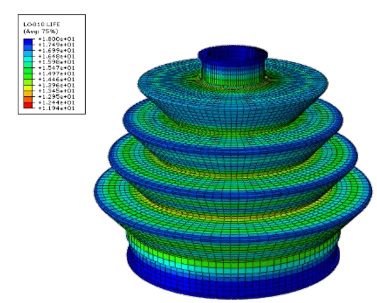




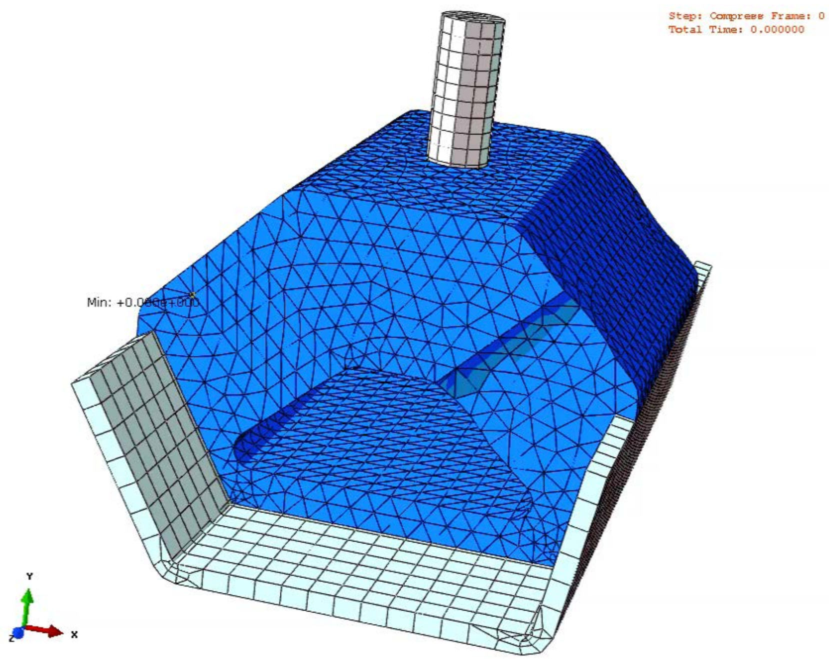
# Most Durable Design Options

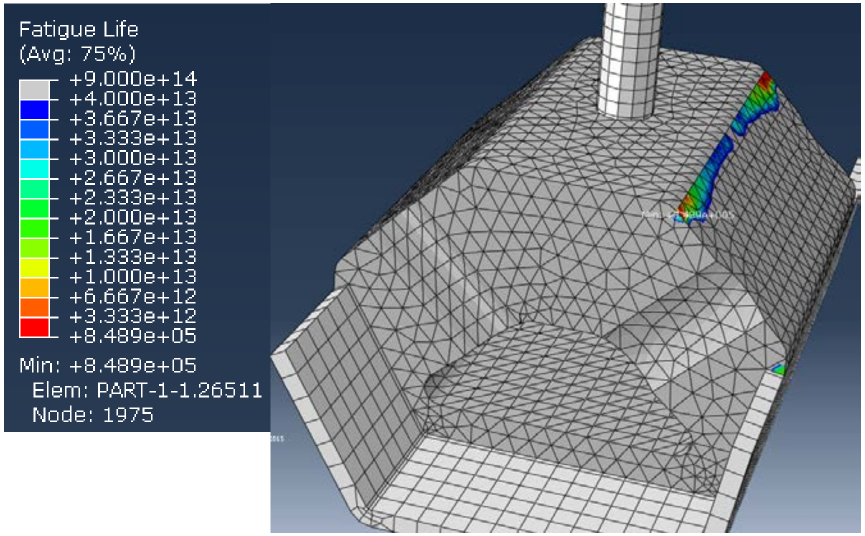




# Cradle Mount



# Challenges / Opportunities

- Be more aggressive with durability/weight optimization
- Avoid risks of probing durability issues only at the conclusion of a development cycle
- Avoid costs of unnecessary development team iteration
- Show your customers that you are in control of durability issues

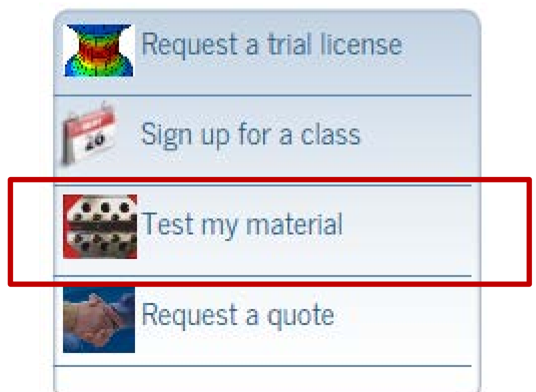
# Forward Paths…




- July 2015: Theory and Application of Rubber Fatigue Analysis with fe-Safe/Rubber (Minneapolis, MN, USA)
- November 2015: Characterizing elastomer fatigue behavior for analysis & engineering, (Ann Arbor, USA)

**Fatigue Property Mapping**

*Know Your Material*




**fe-safe/Rubber**

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