

Endurica

Accelerating Reliable Design

Fatigue Life Prediction for Elastomers

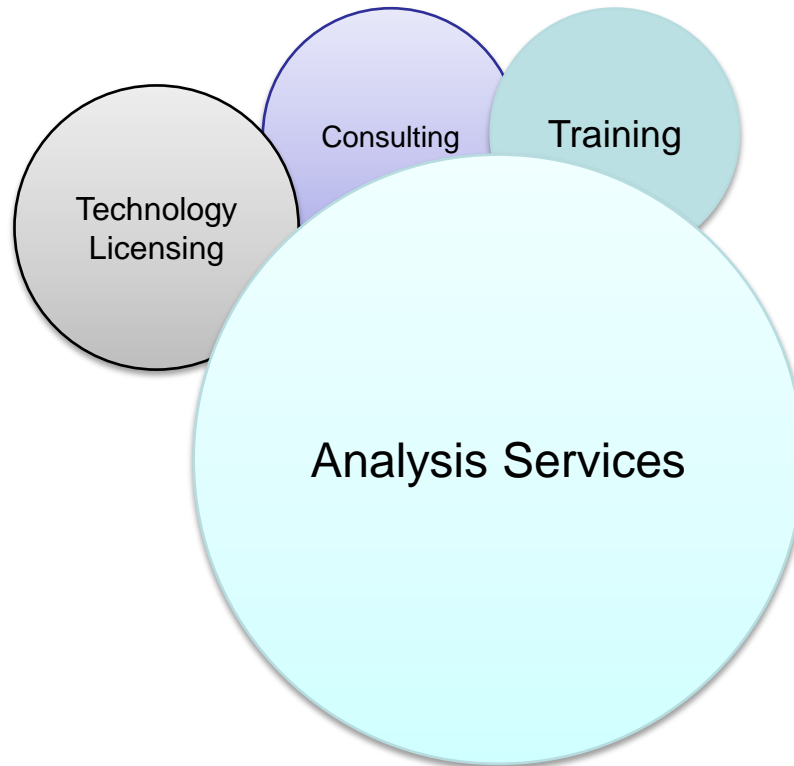
www.endurica.com



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.

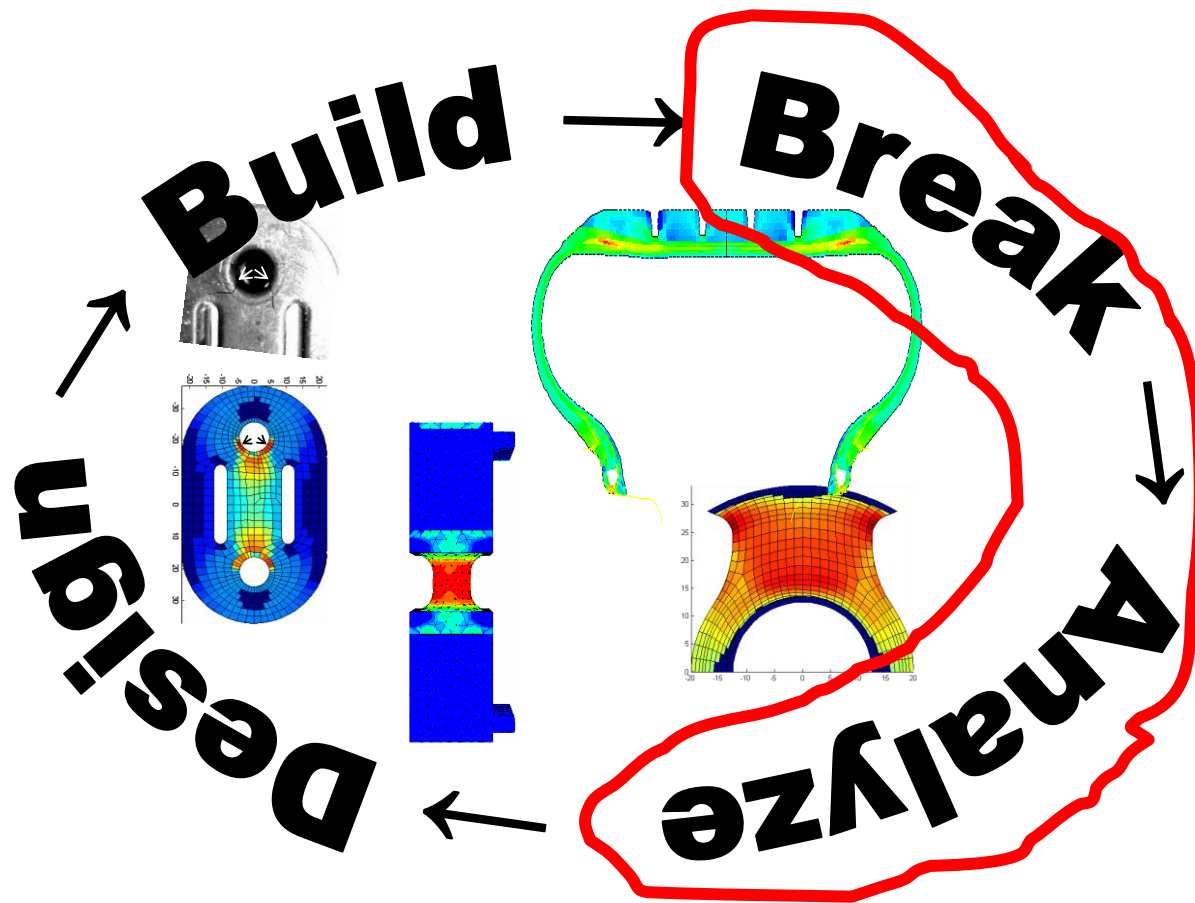
About Endurica –Business Model



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

Developing a Rubber Component

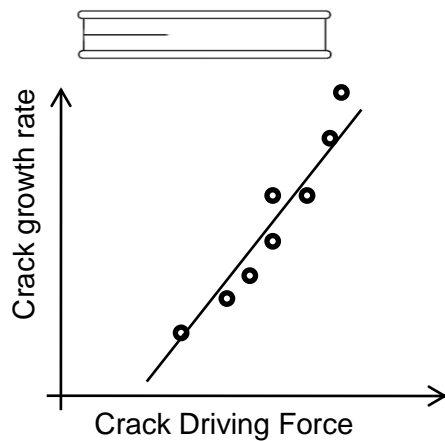
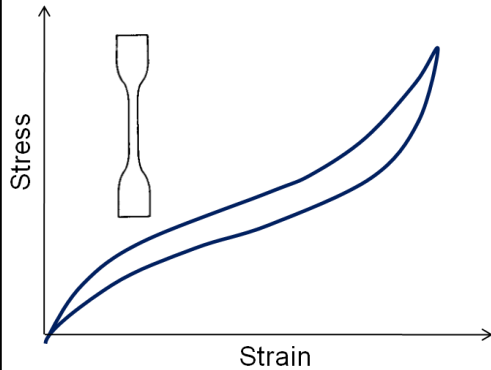


Industry Sectors:

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

Analysis Paradigm

Material Properties



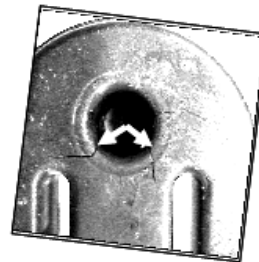
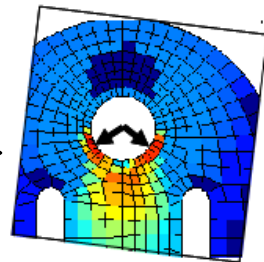
Because of their macromolecular structure, elastomers exhibit unique behavior and require specialized analysis methods.

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

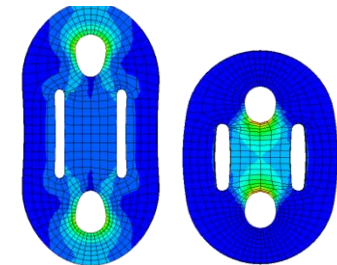
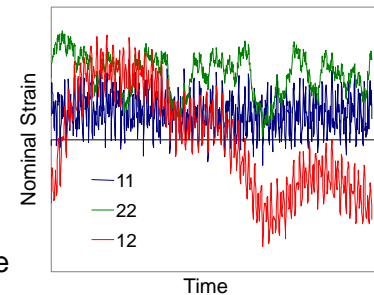
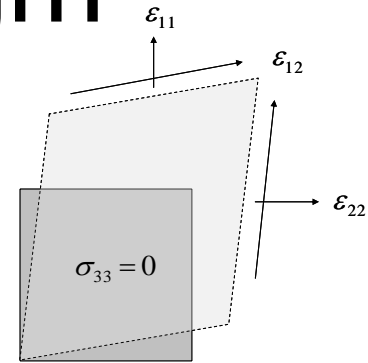
Given the material properties and duty cycle of a rubber component, the number of cycle repeats that will be endured before fatigue failure can be computed.

Endurica considers the factors that distinguish elastomers:

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



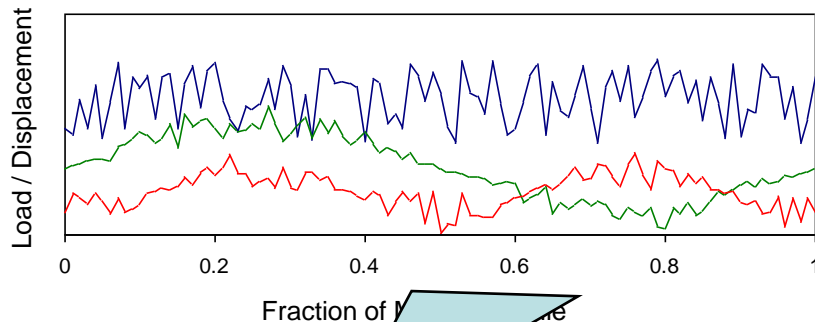
Fatigue Life Prediction



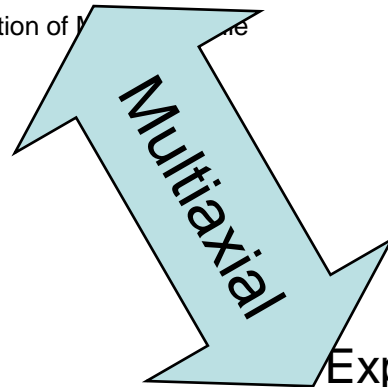
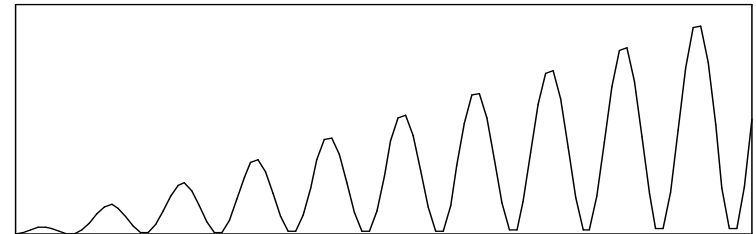
Duty Cycle

Analysis Issues

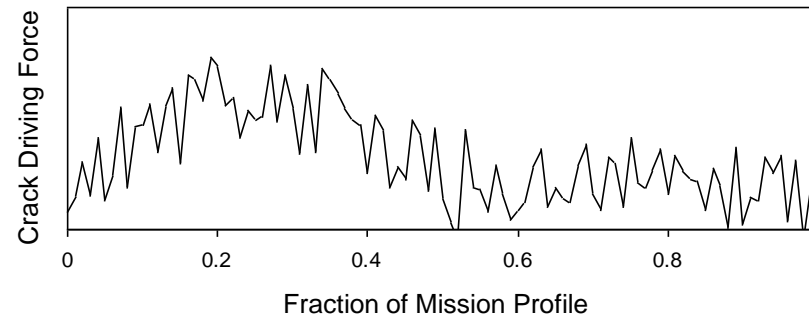
Applied to Structure



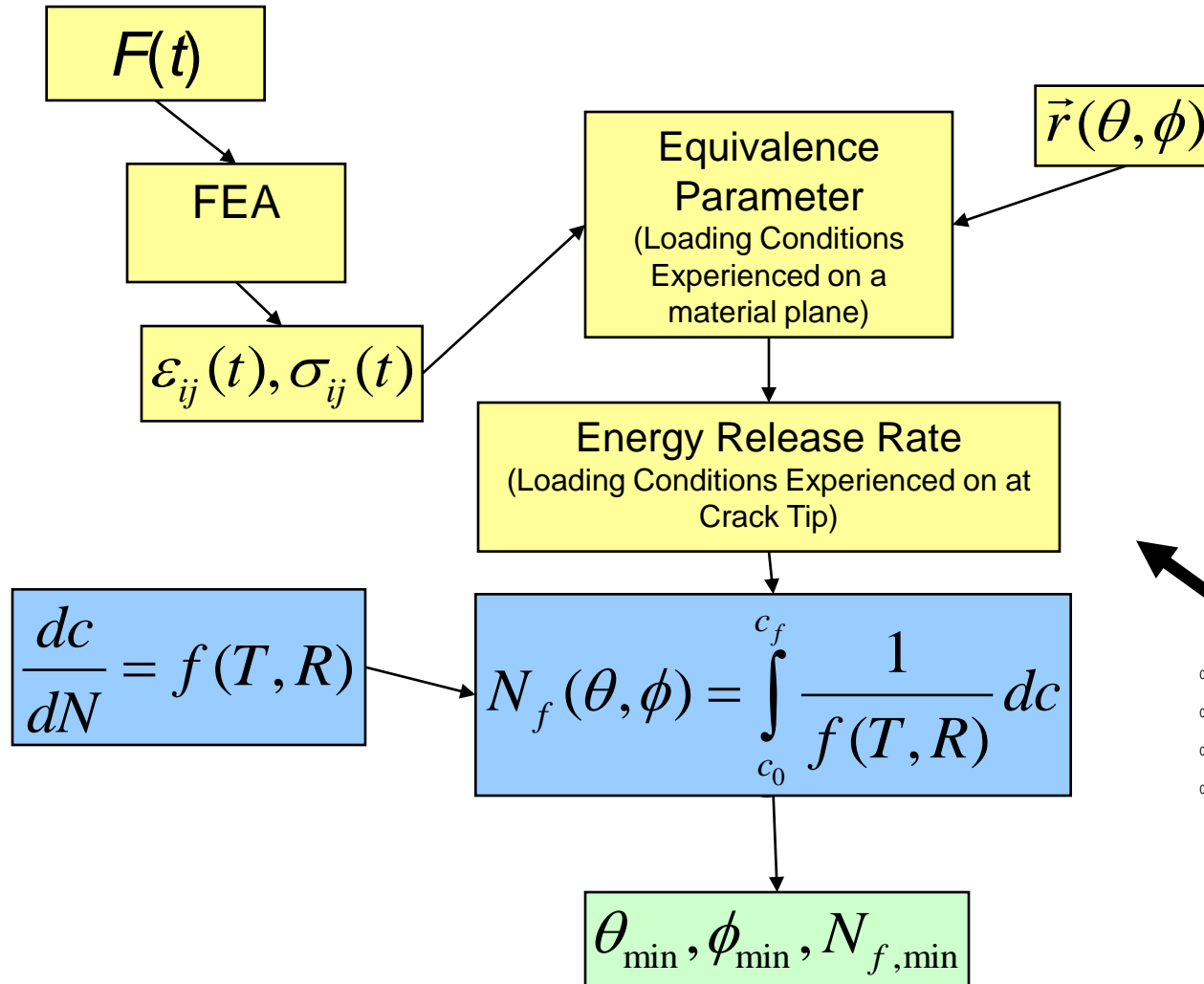
Material Characterization



Experienced by Crack

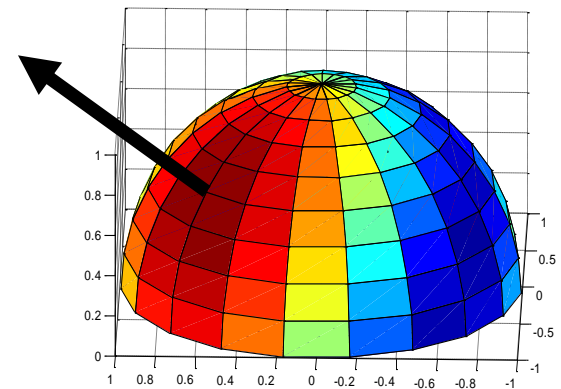


Life Calculation Scheme



Deals with:

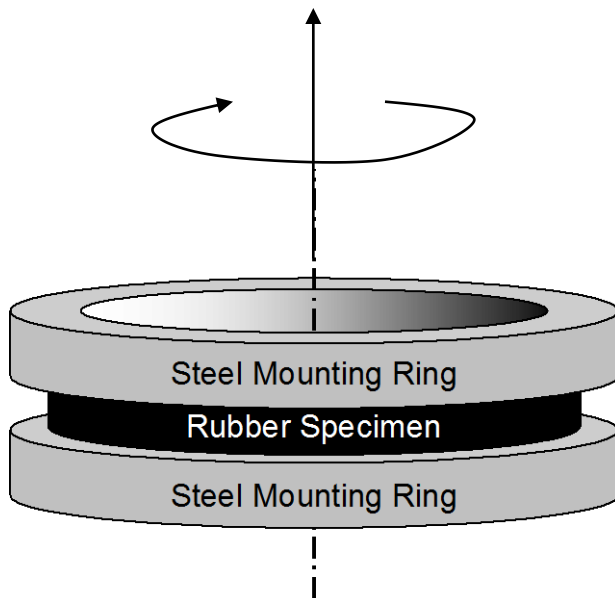
- Crack closure
- Multiaxiality
- Critical plane
- Nonlinear elasticity
- FCG behaviors unique to elastomers



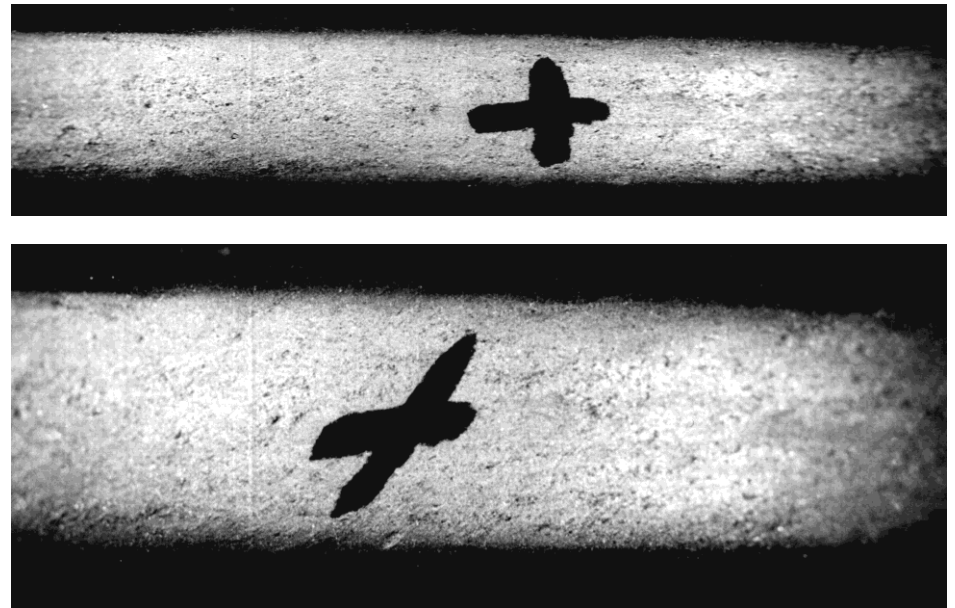
Validation Experiences

Axial / Shear Fatigue Experiments

NR + 60 phr N650

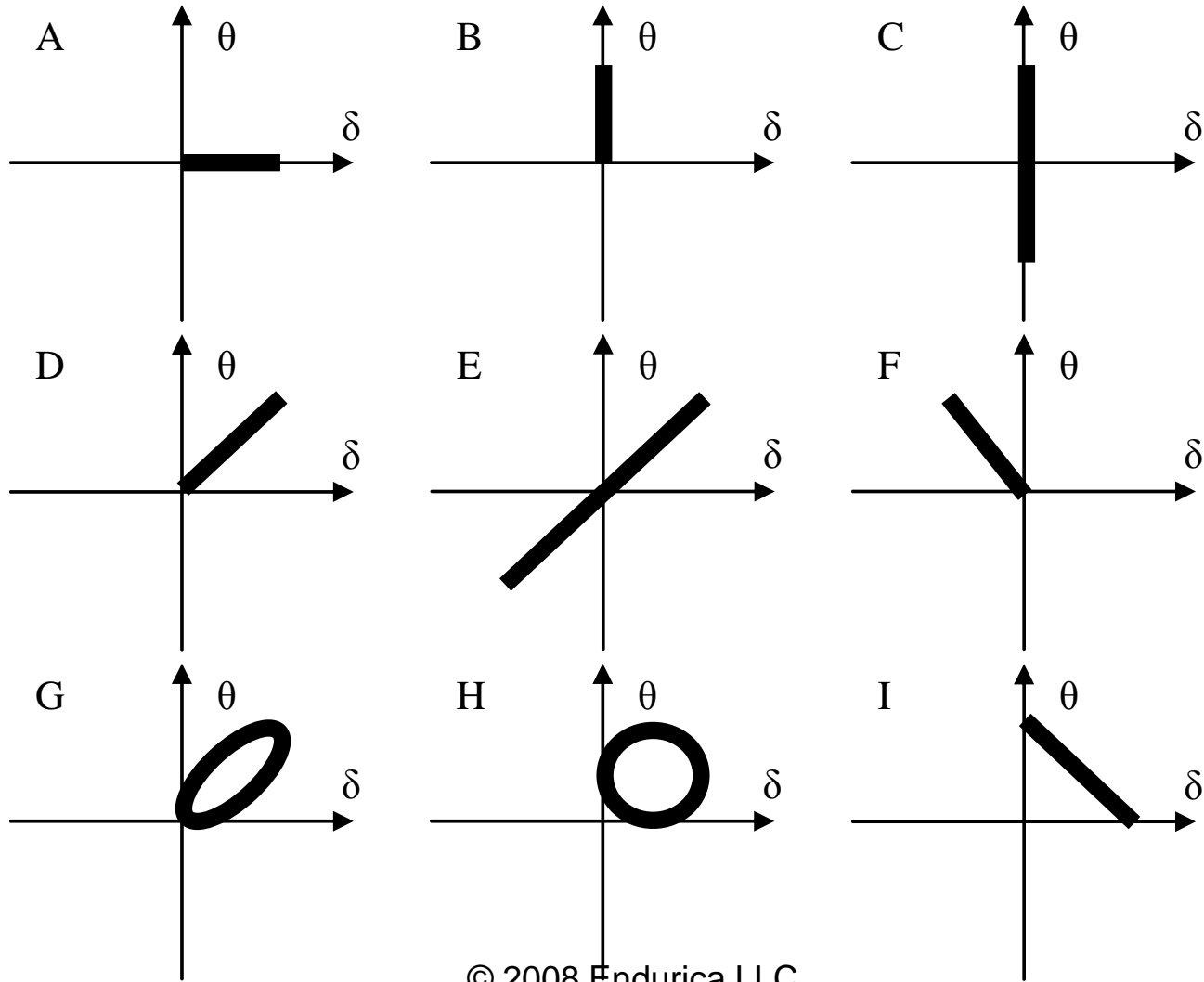


Test Specimen



Mars, W.V., Fatemi, A., 2004. A Novel Specimen for Investigating Mechanical Behavior of Elastomers under Multiaxial Loading Conditions, *Experimental Mechanics*, 44: 136-146.

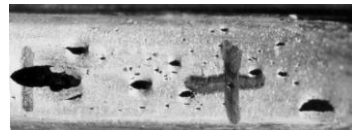
Loading Paths Investigated



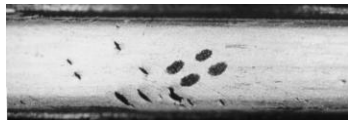
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Multiaxial Fatigue of Rubber, W. V. Mars, Ph. D. Dissertation, University of Toledo, 2001.

Cracking Plane Observations



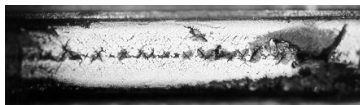
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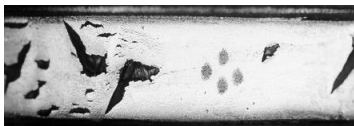
B



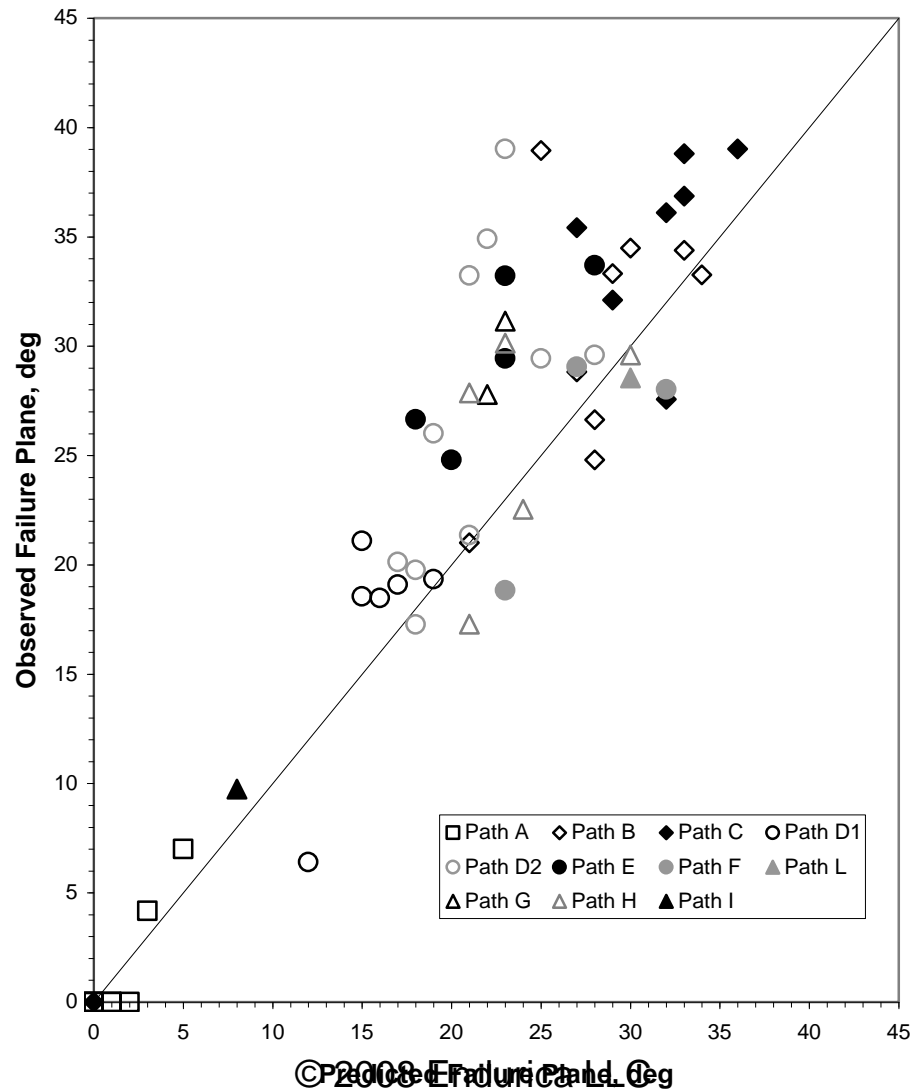
C



J



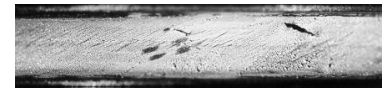
K



D



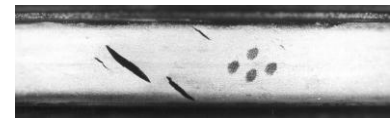
E



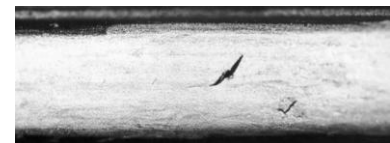
F



G

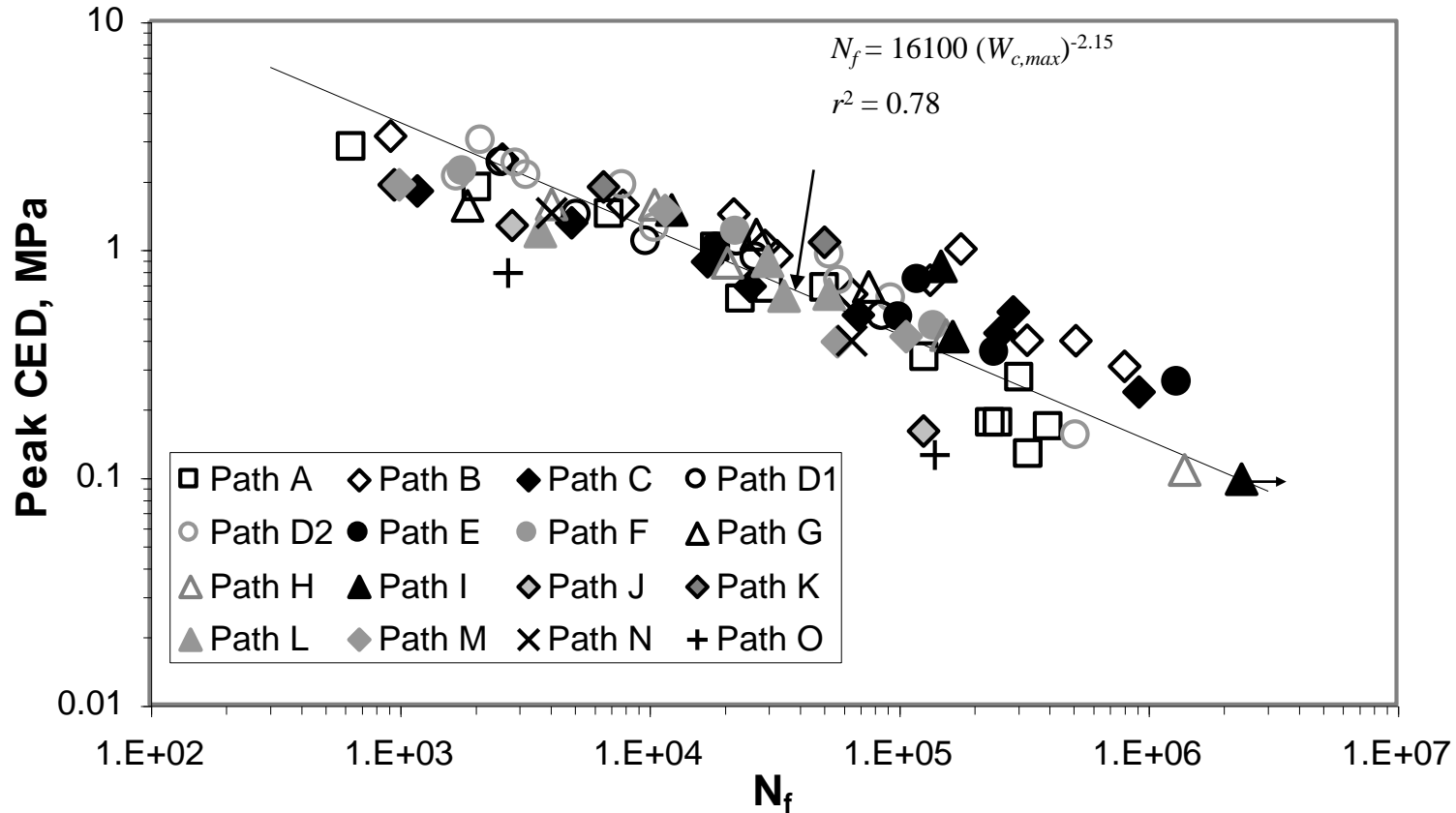


H



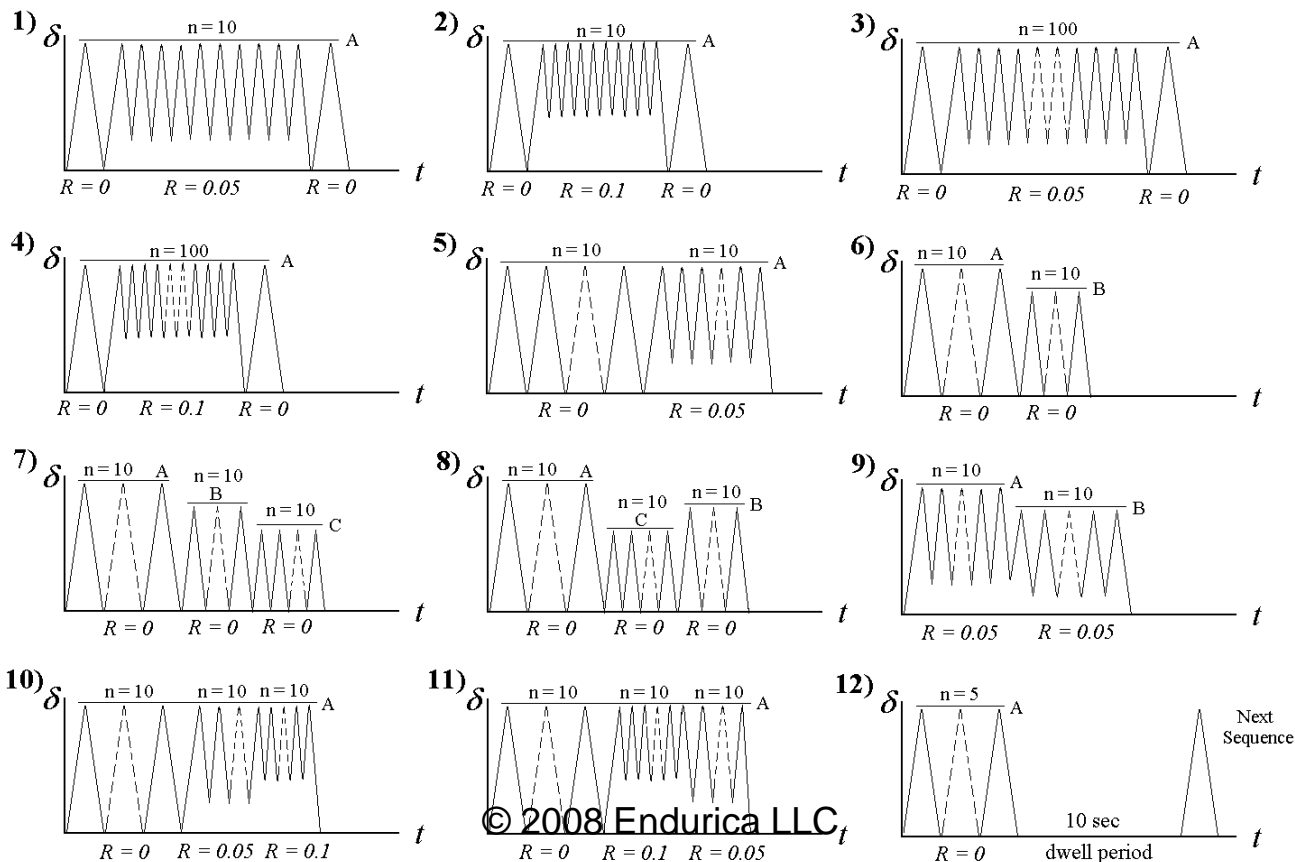
I

Multiaxial Fatigue Life Correlation

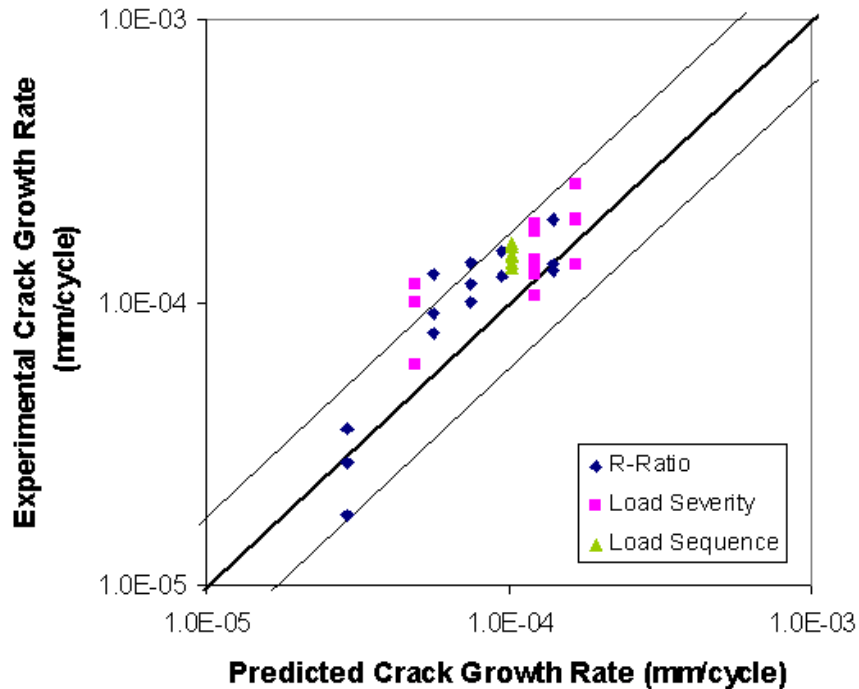


Variable Amplitude Test Signals

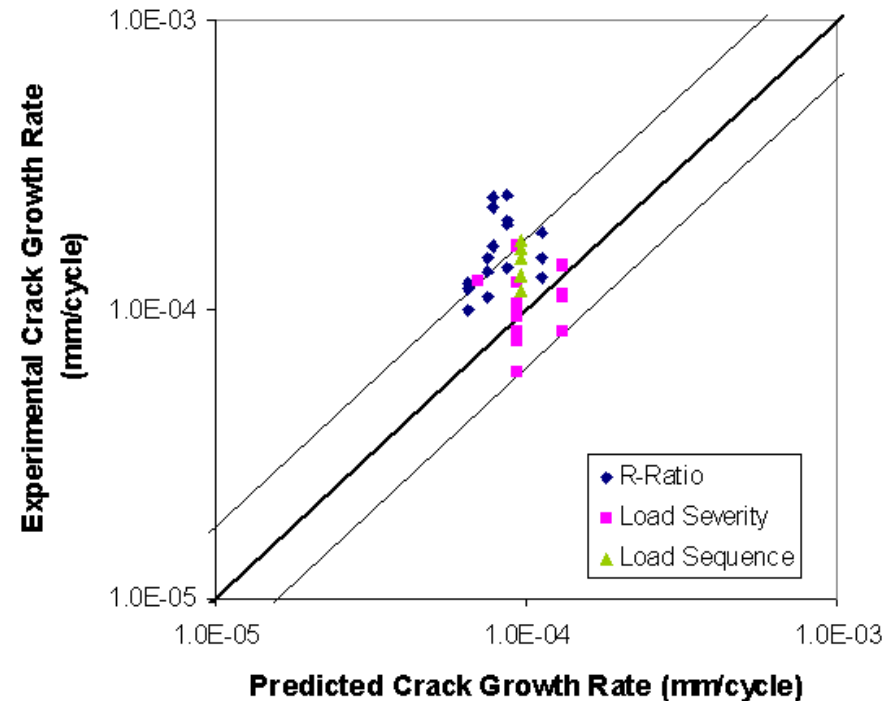
- Signals vary R -ratio, load severity, and load sequence in a repeated block format



Variable Amplitude Results

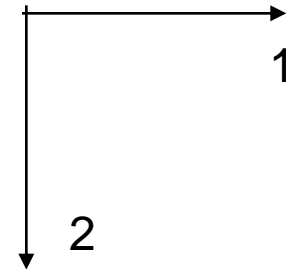
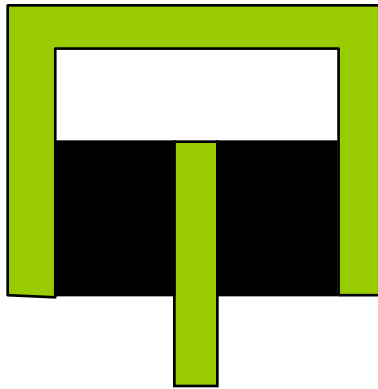


Natural Rubber

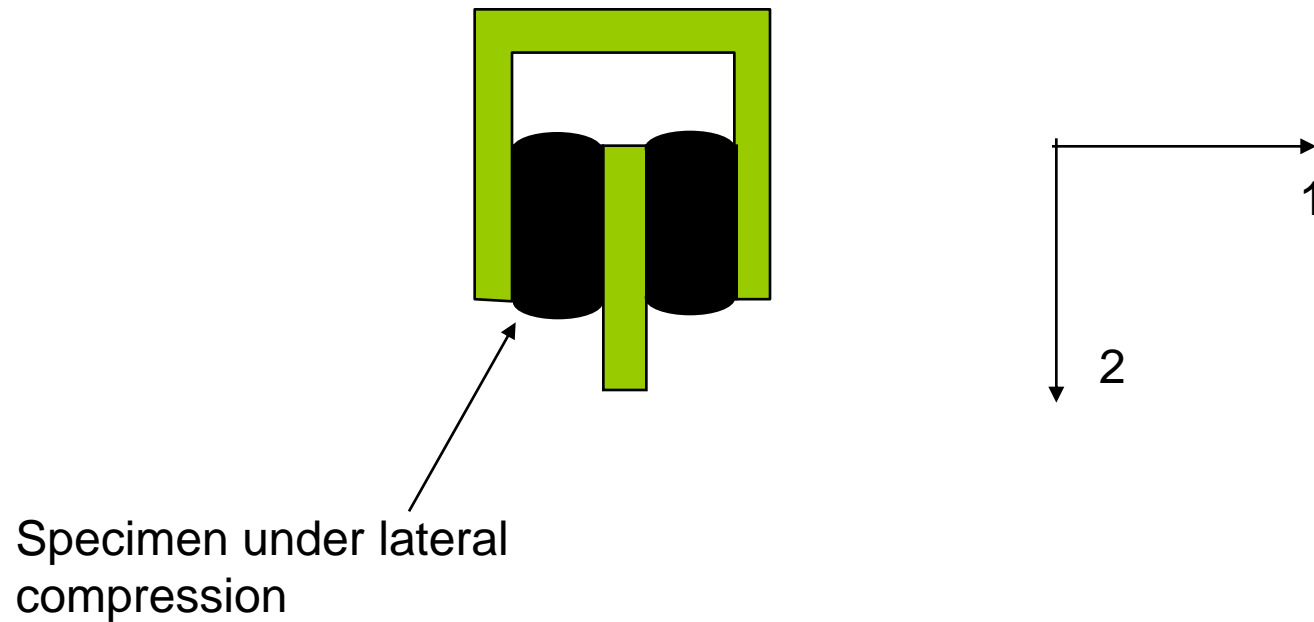


SBR

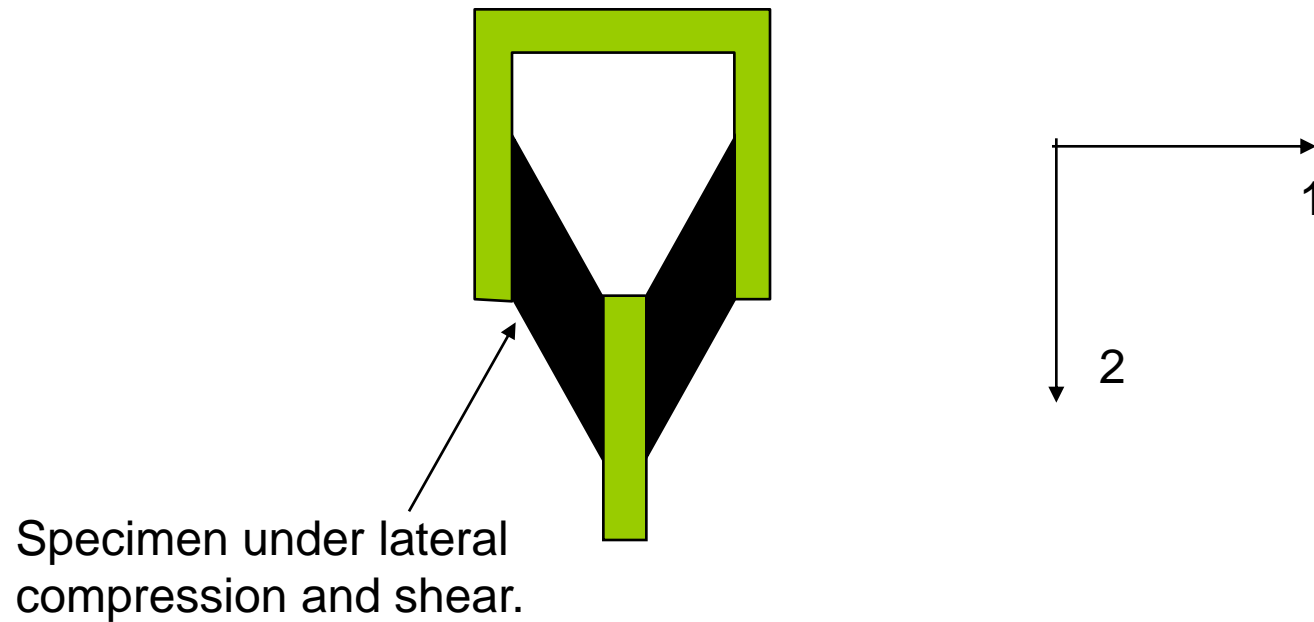
Cadwell's Test Specimen



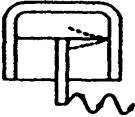
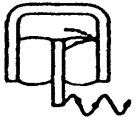
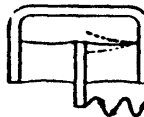


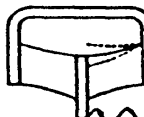



Cadwell's Test Specimen



Cadwell's Test Specimen



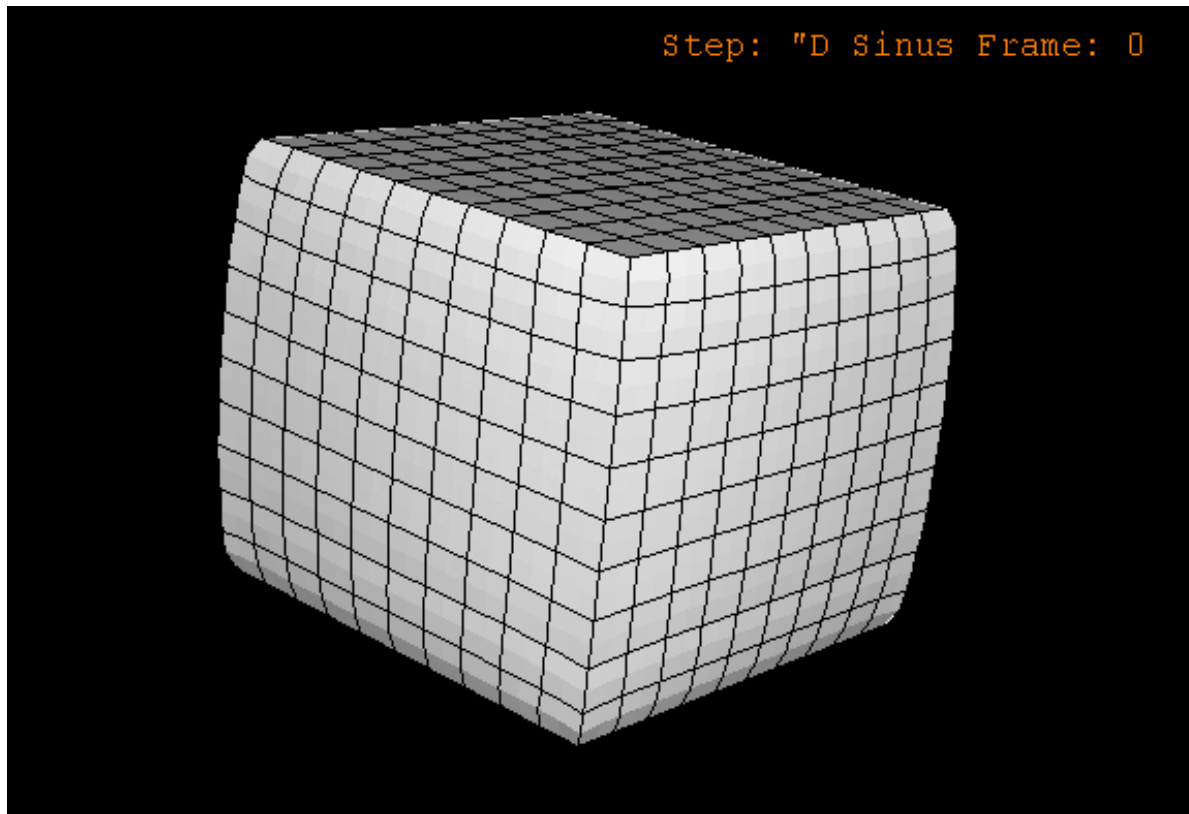
Experimental Results

SHEAR CYCLE	LATERAL STRAIN		
	NONE	12½% COMPRESSION	25% EXTENSION
-25% TO +25%	A  7-MILLION	D  20-MILLION	G  12-MILLION
0% TO 50%	B  1-MILLION	E  2-MILLION	H  2-MILLION
75% TO 125%	C  15-MILLION	F  2-MILLION	I  40-MILLION

- **Loading**
 - Compression / Tension
 - Cyclic Shear
- **R Ratio**
 - Fully Relaxing (R = 0)
 - Non-Relaxing (R > 0)
- **Long Fatigue Life**
 - Threshold Effects
 - Ozone attack

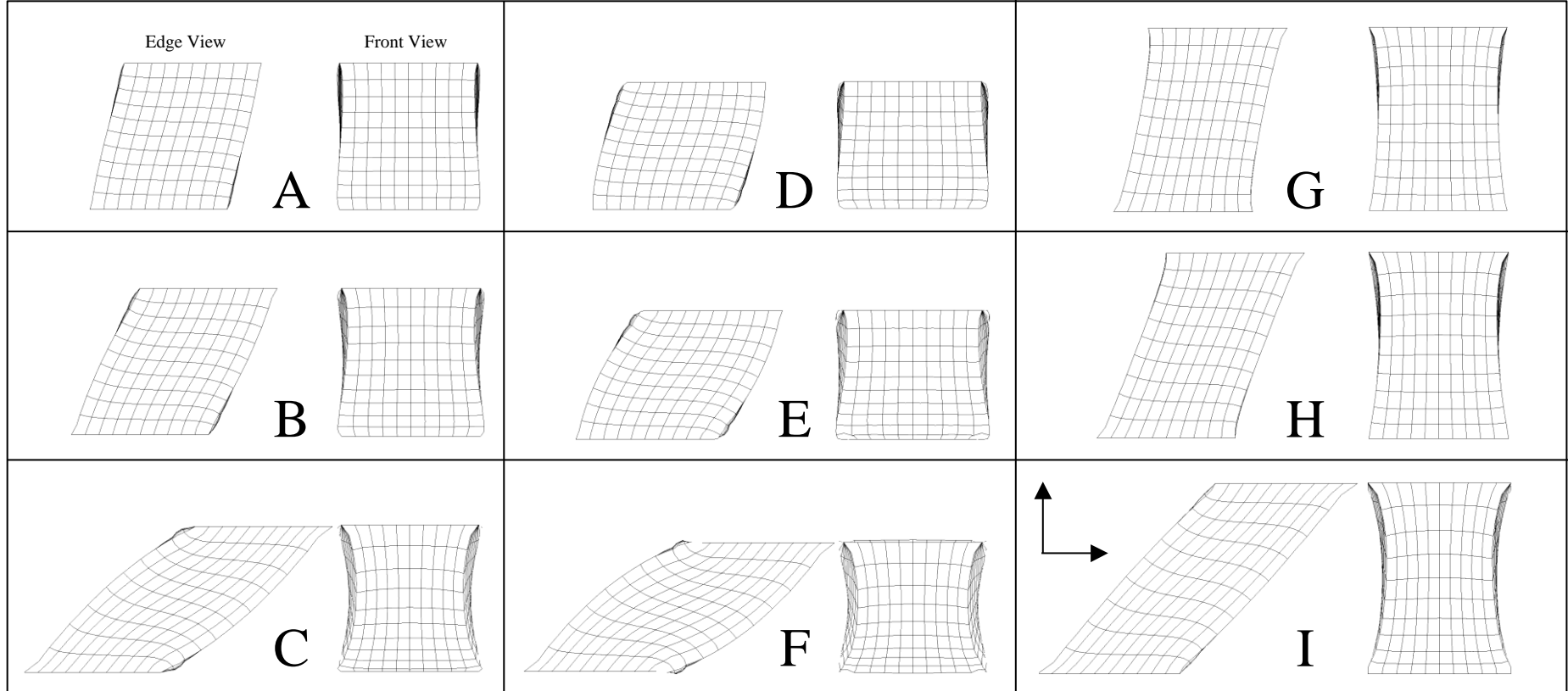
COMPLEX!

Finite Element Analysis

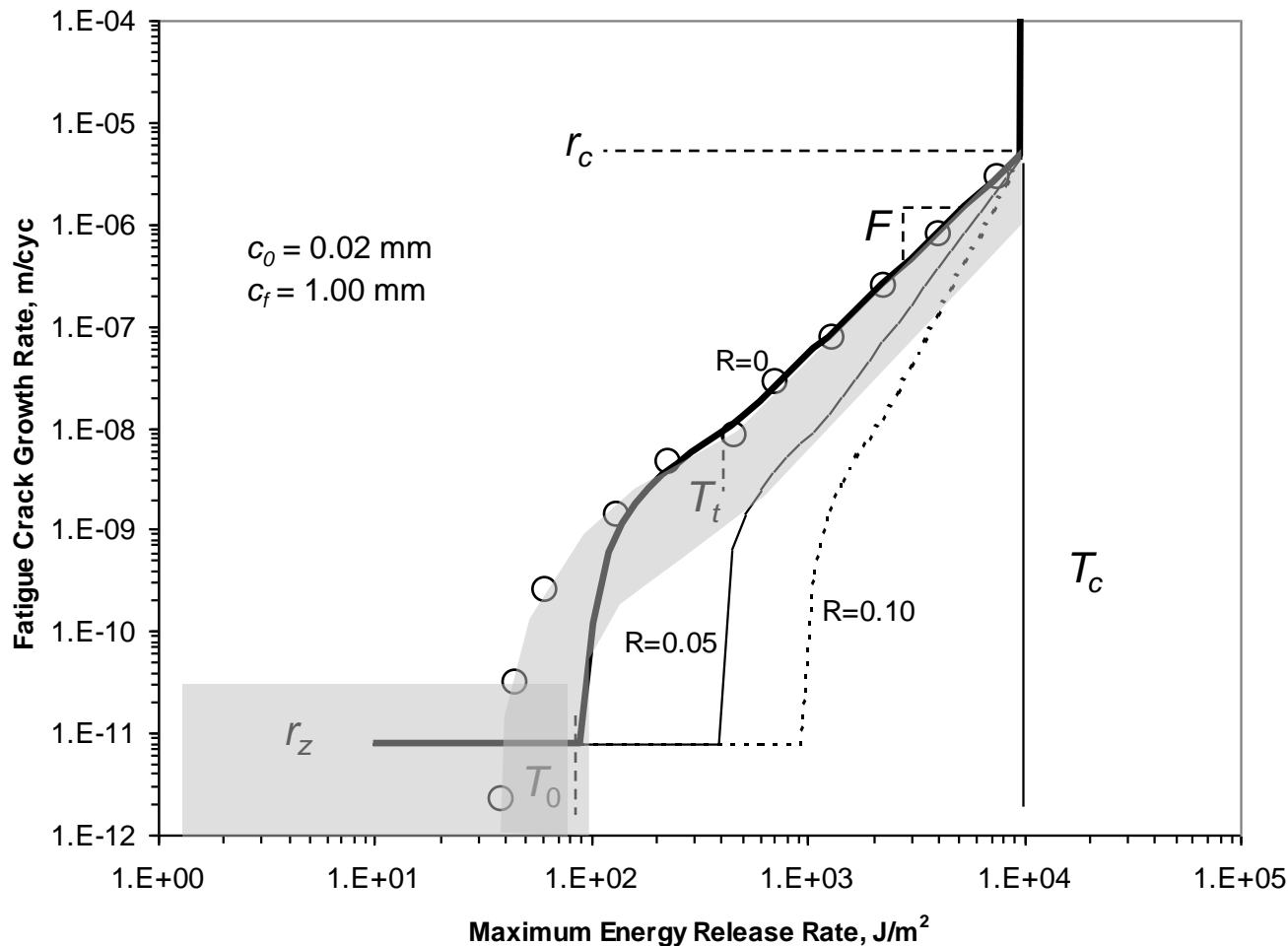


- 10 x 10 x 10 mesh
- 3-D, 2nd order, hybrid formulation, reduced integration elements (C3D20RH)
- Neo-Hookean constitutive model, $C_{10} = 0.5$ MPa
- Sinusoidal Cyclic Shear Loading
- Strain History Recovery: Element Centroids

Finite Element Analysis



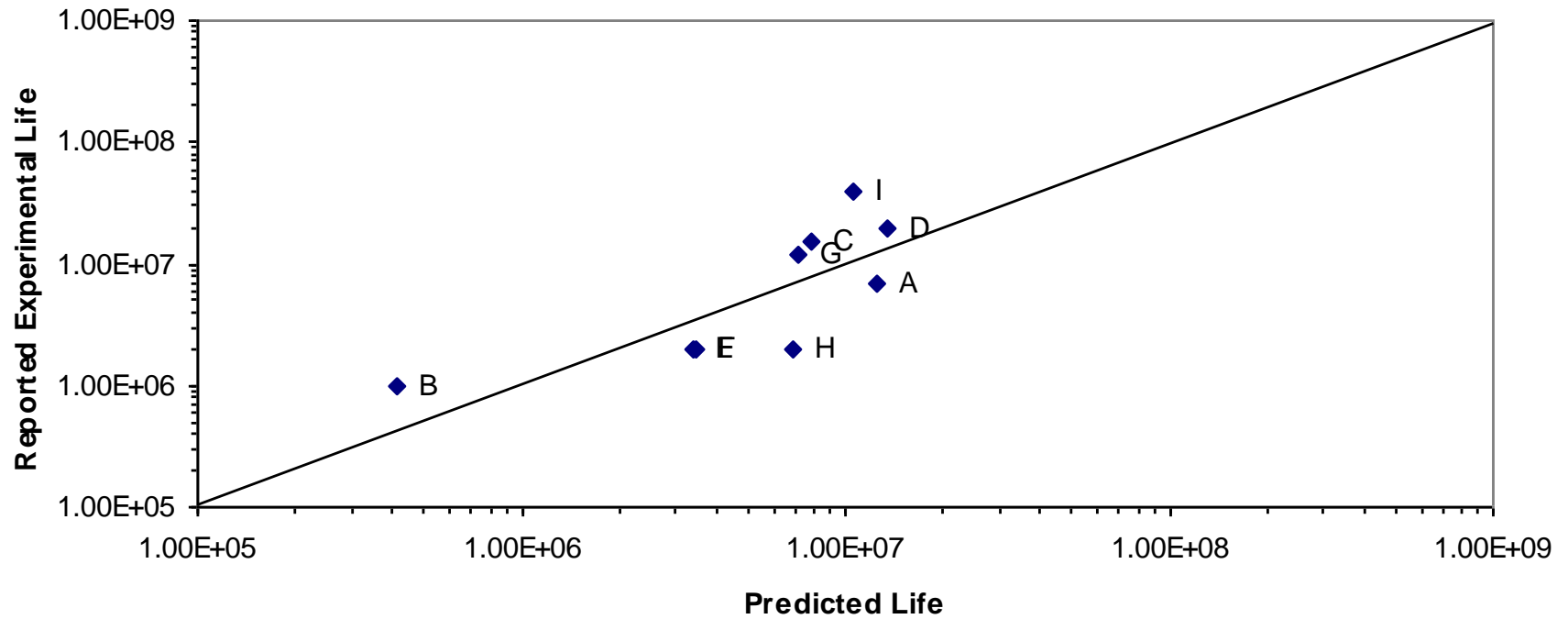
Crack Growth Properties



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

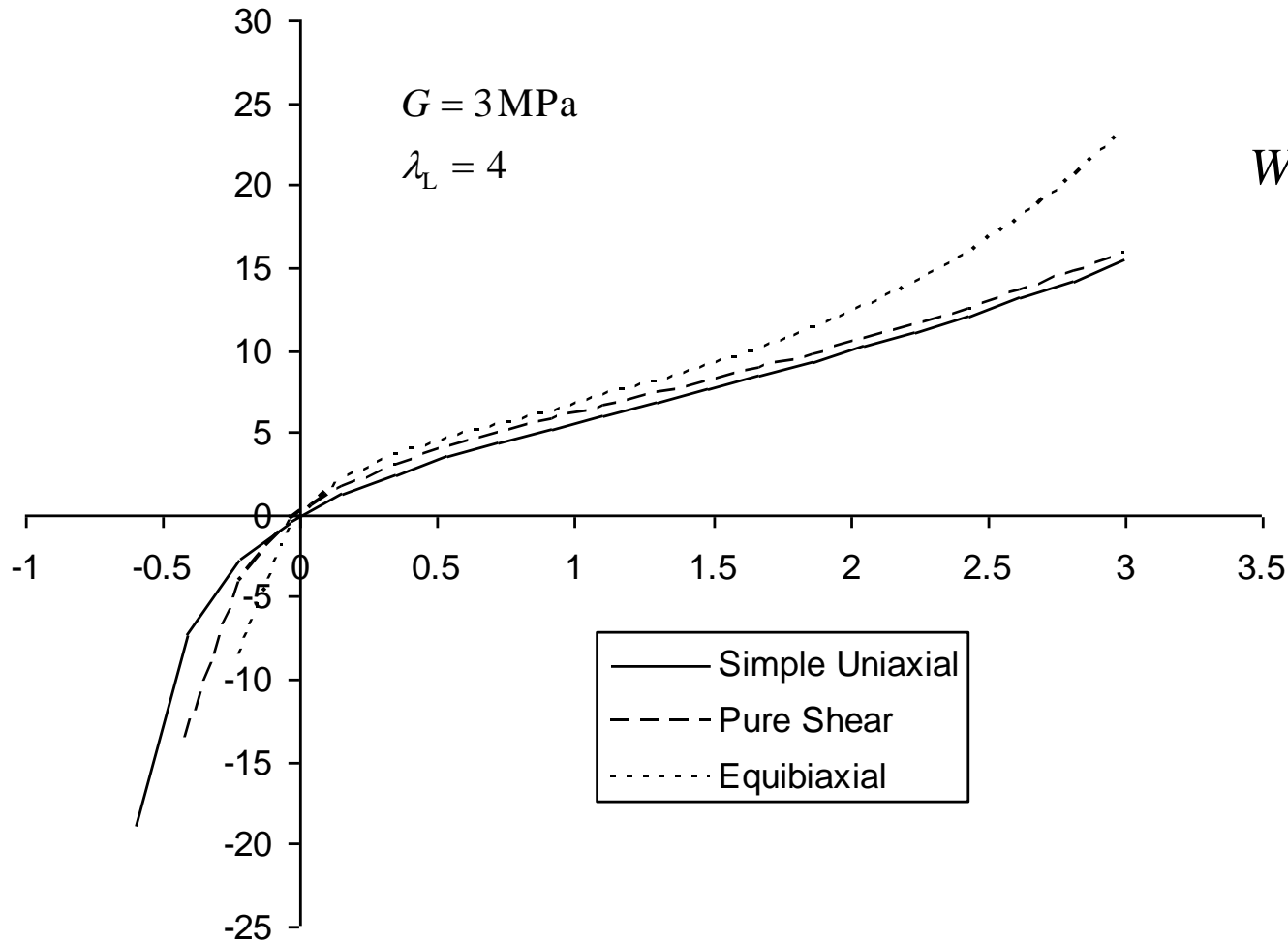
$$F(R) = Fe^{CR}$$

Results



Material Characterization

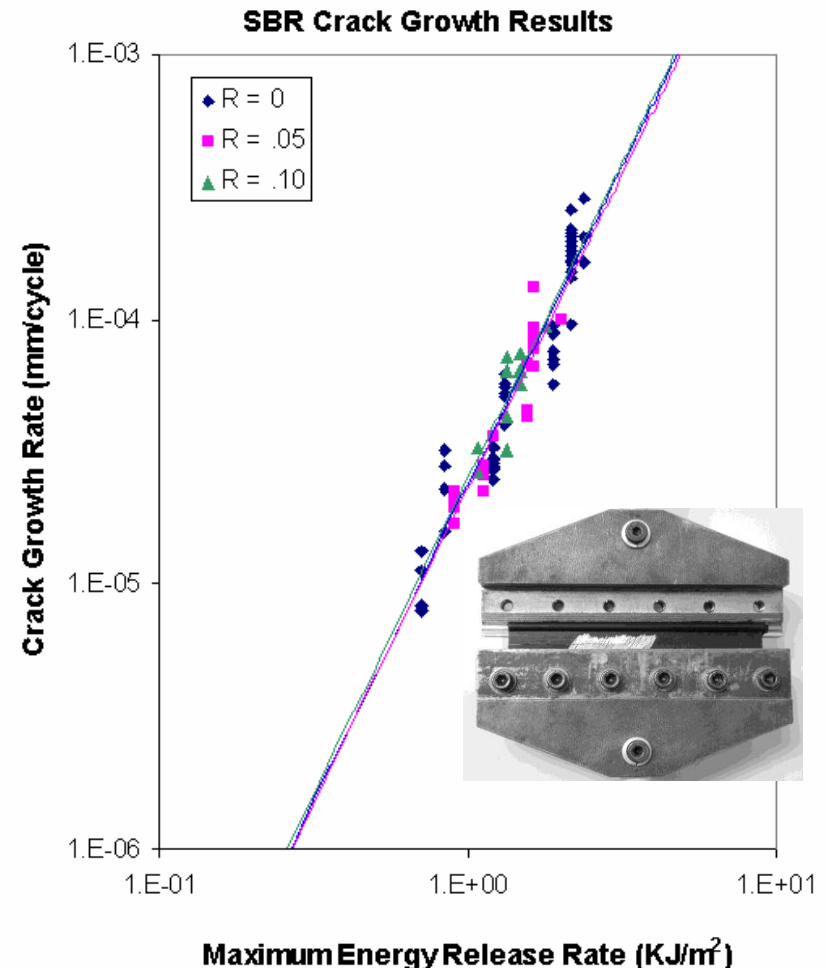
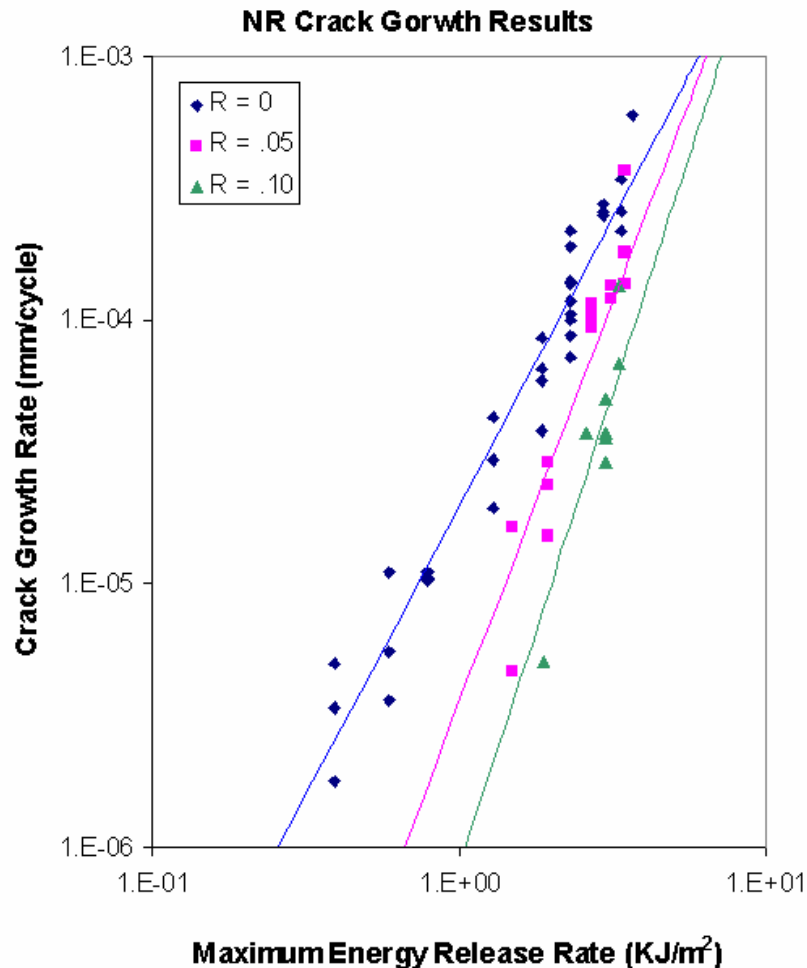
Stress-Strain Behavior



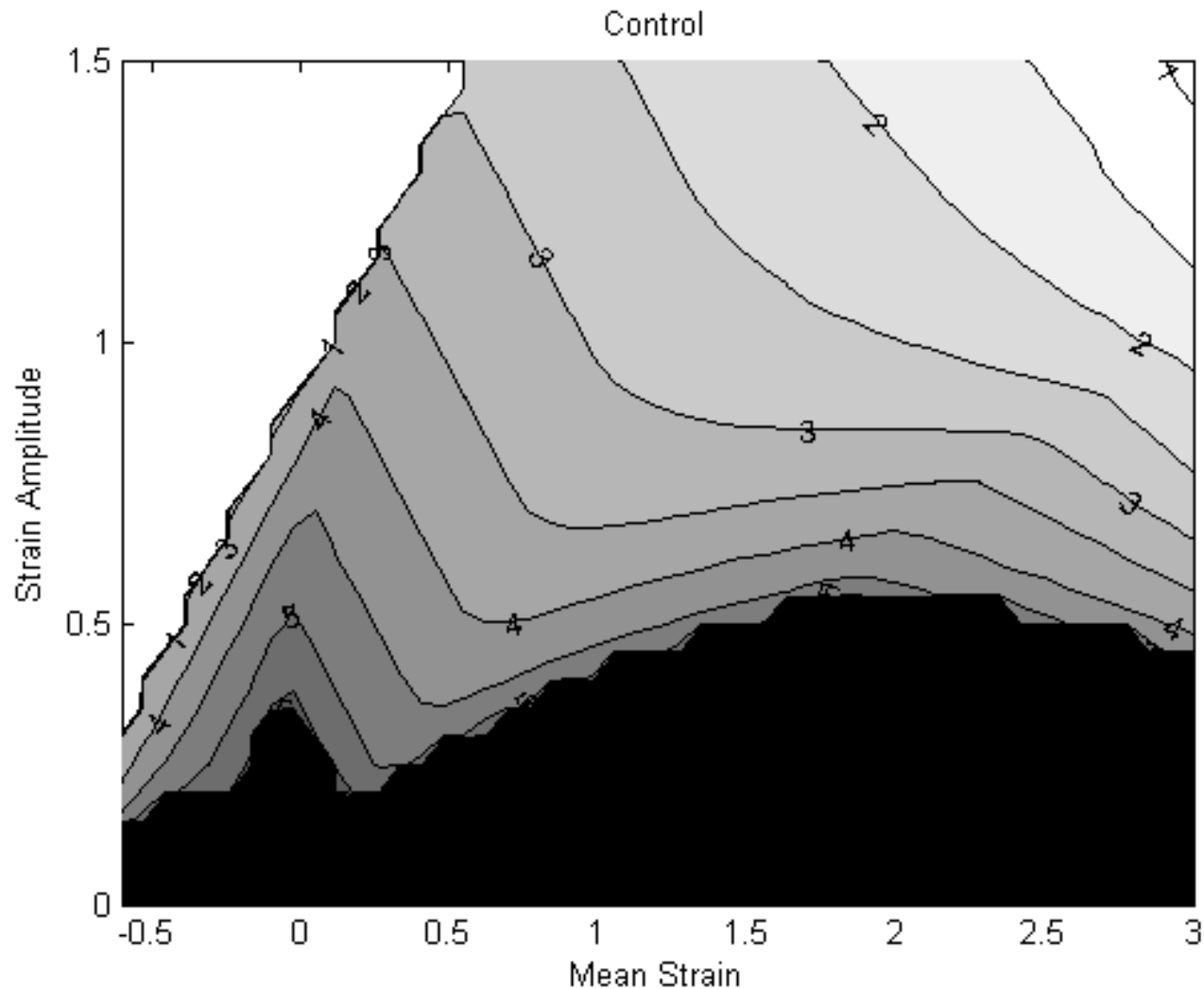
$$W = G \sum_{i=1}^5 \frac{C_i}{\lambda_m^{2i-2}} (\bar{I}_1^i - 3^i)$$

Arruda-Boyce
potential

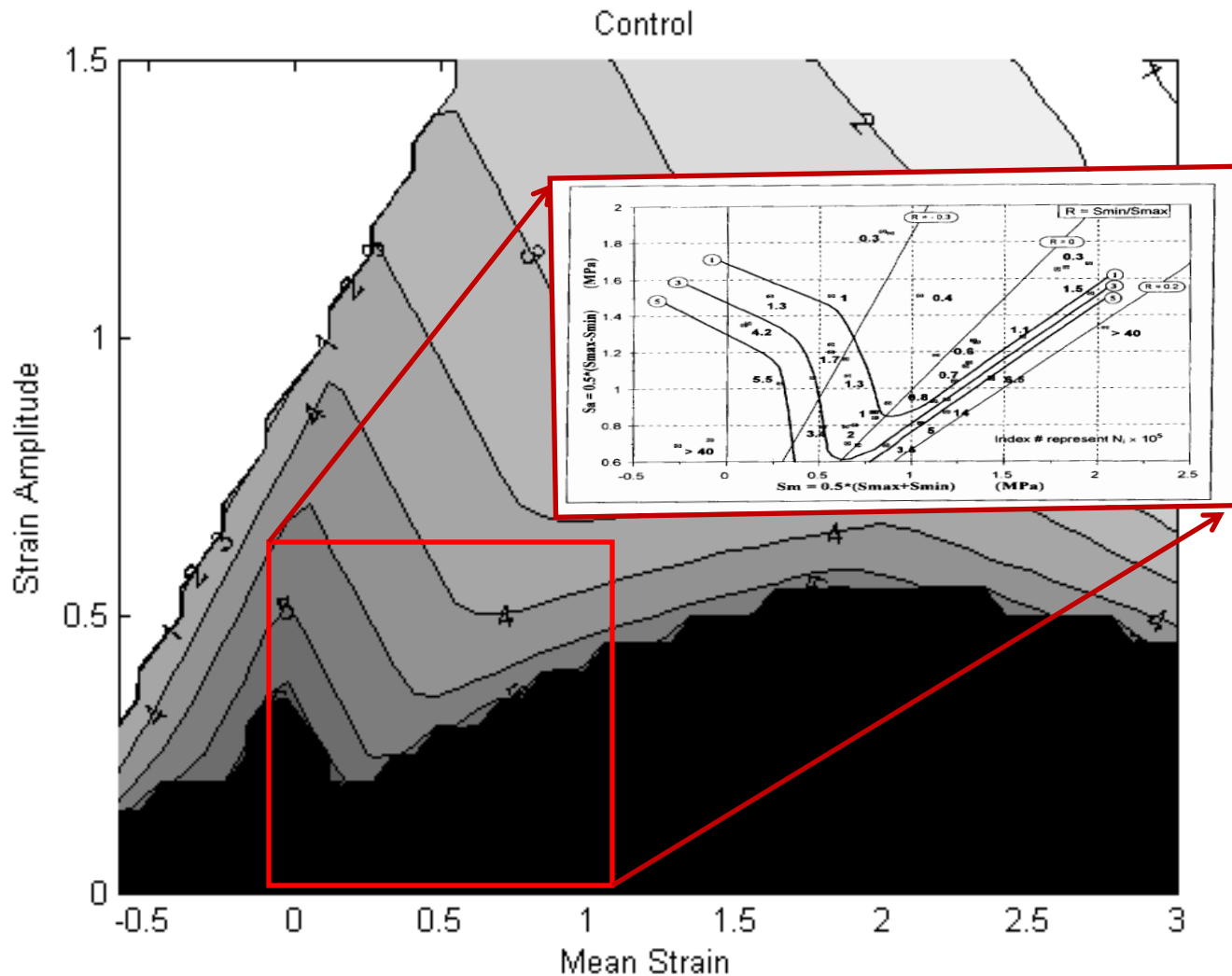
Effect of Strain Crystallization on FCG Rate



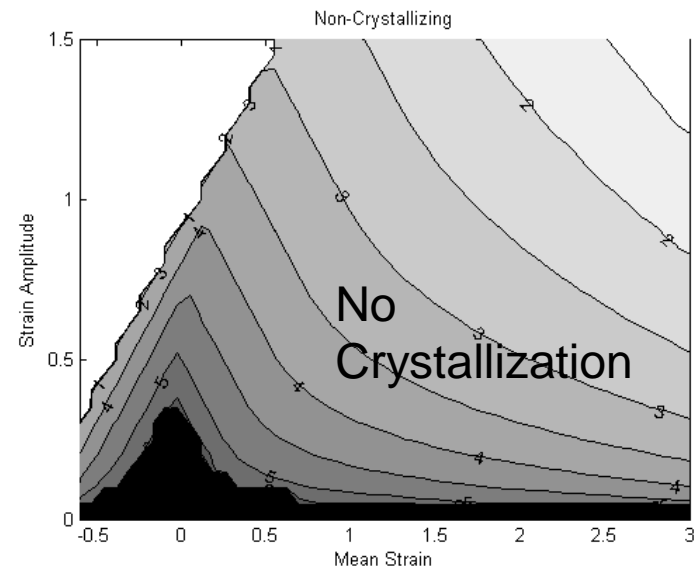
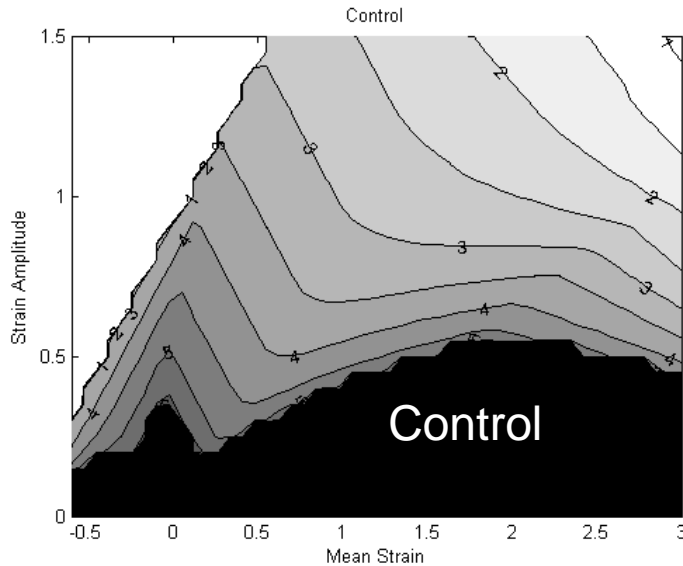
Typical Computed Haigh Diagram



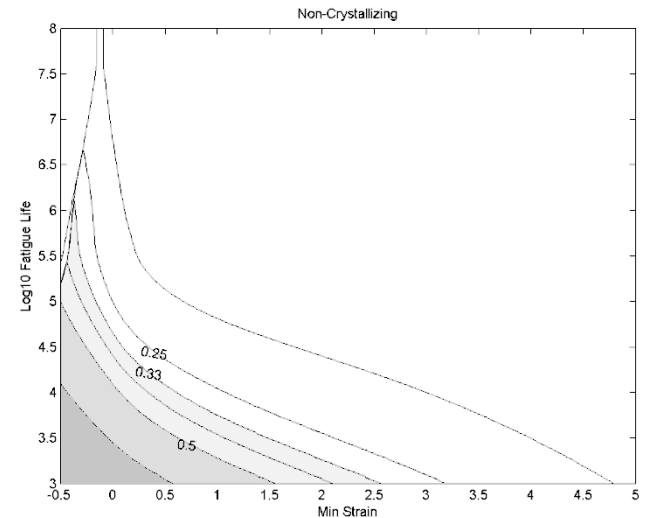
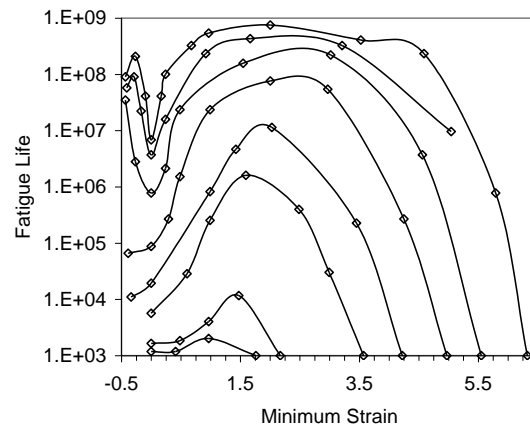
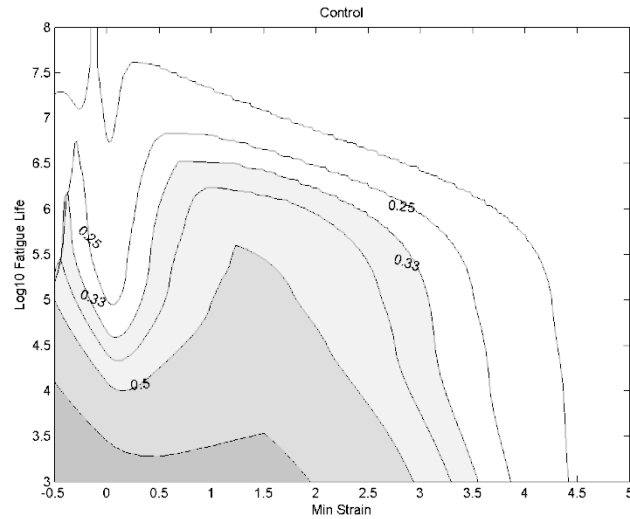
Match to known behavior



Comparing Haigh Diagrams

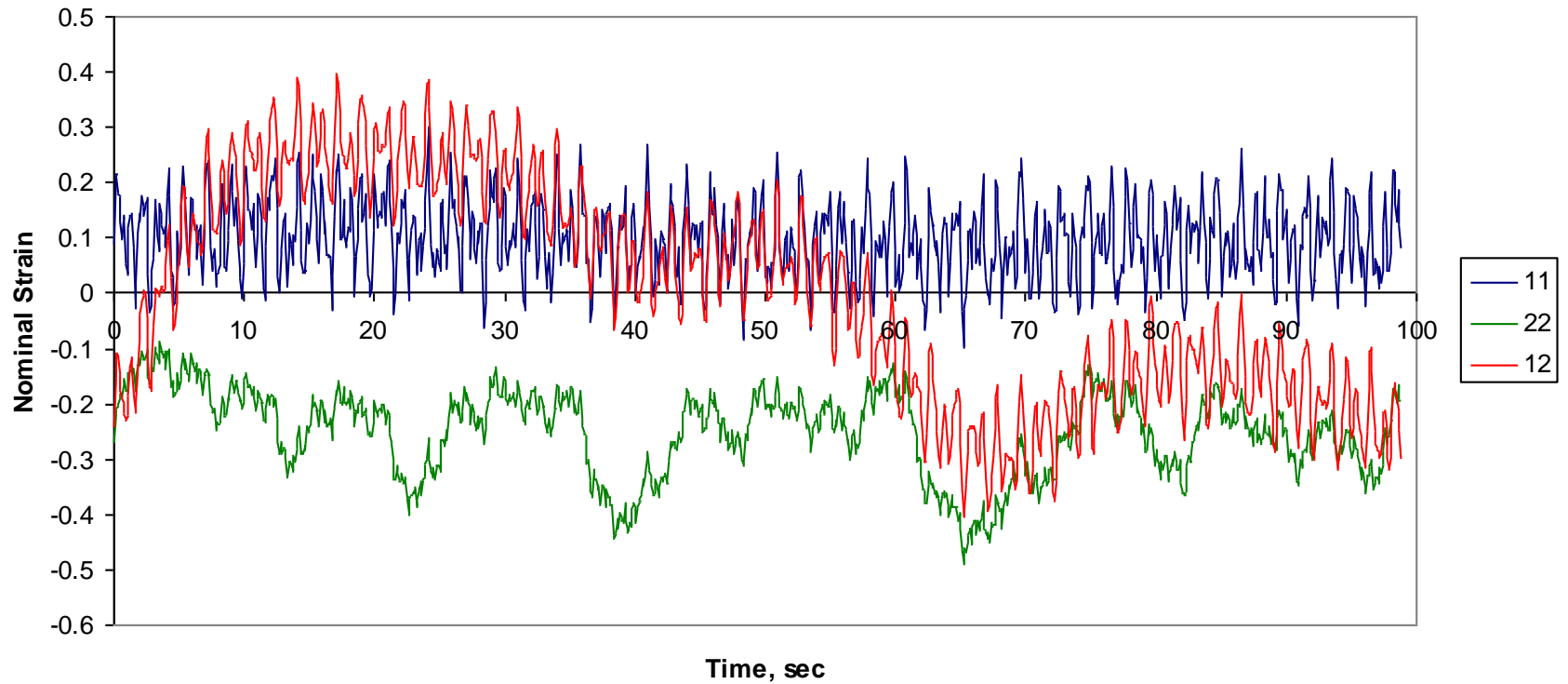


Comparing Cadwell Diagrams

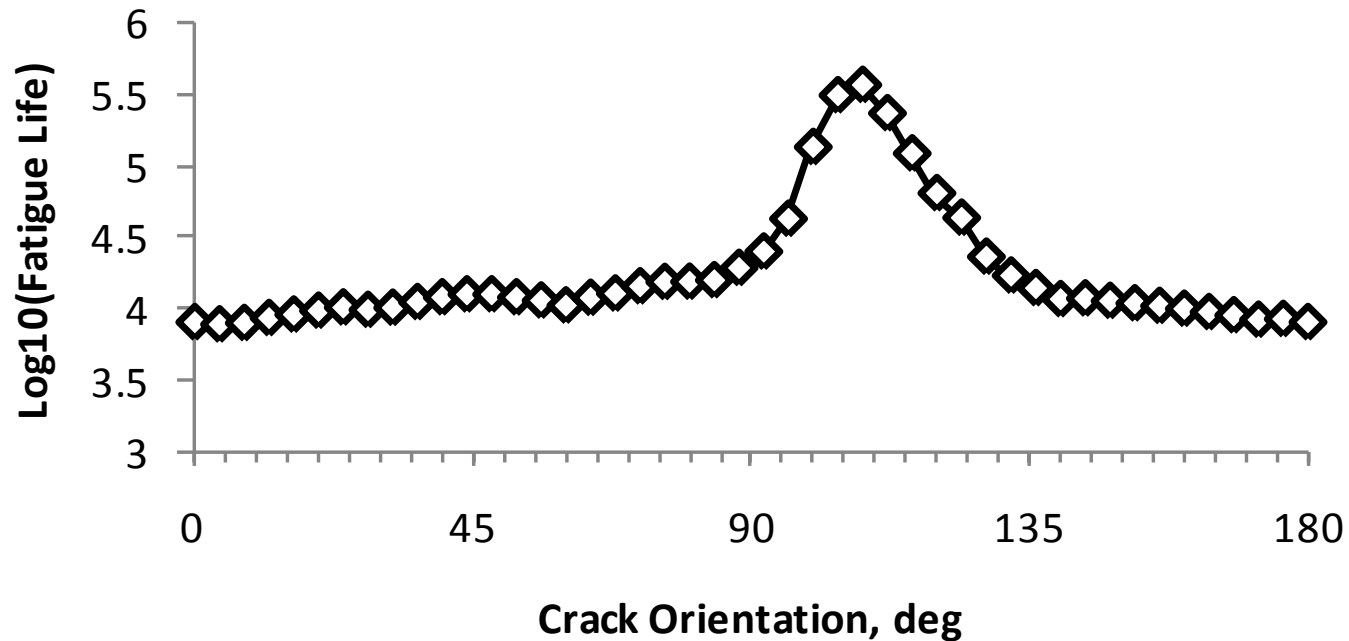


Duty cycle analysis

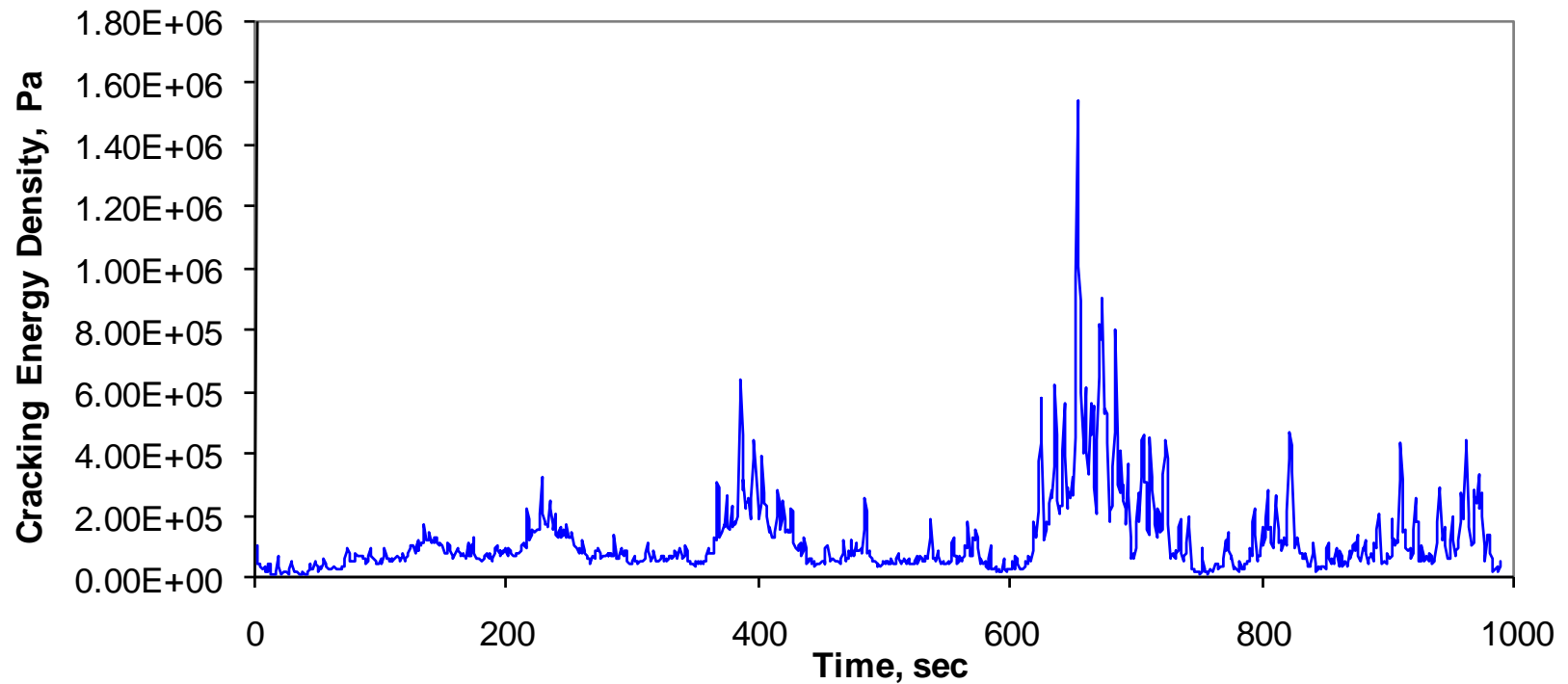
Multiaxial Input



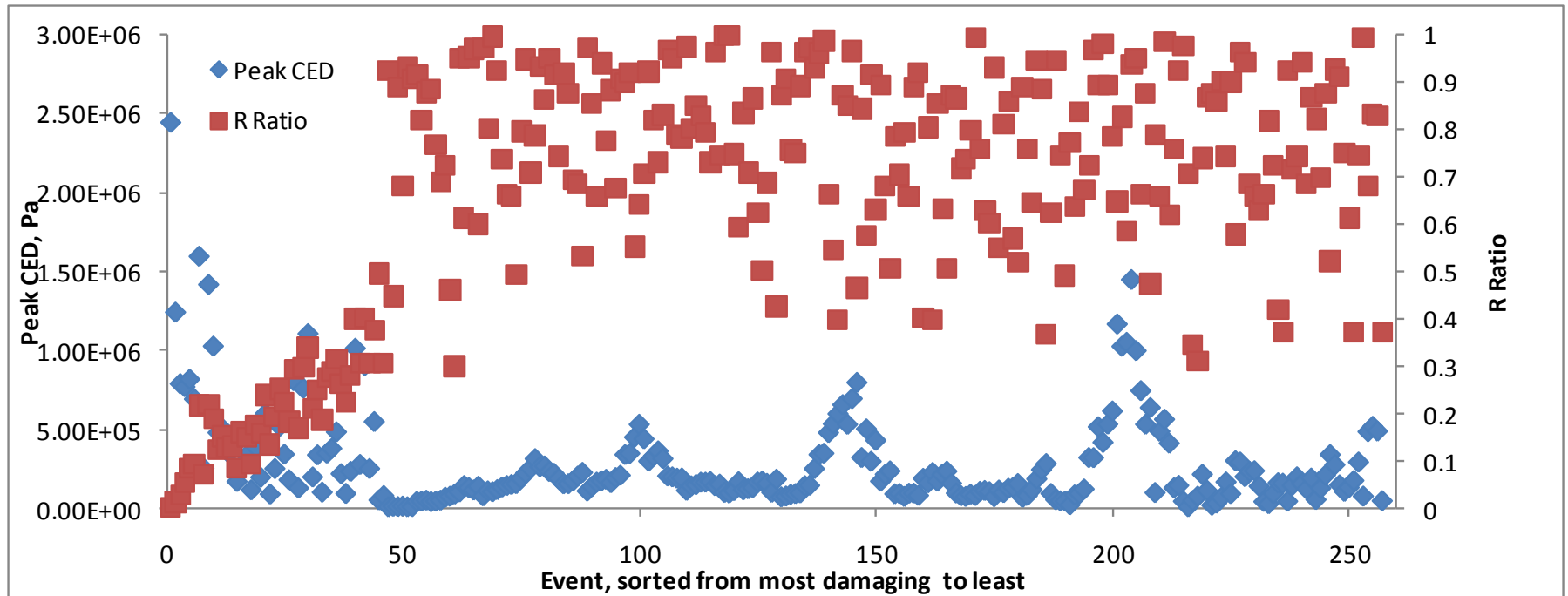
Identification of Critical Plane



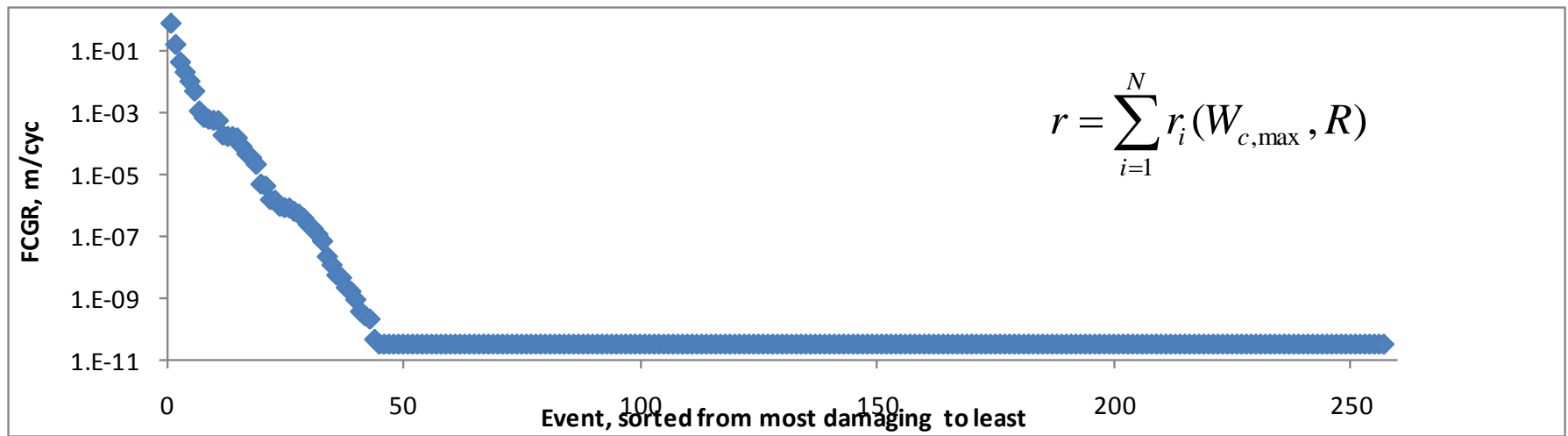
Crack Plane Experience



Rainflow Count Results – Peak and R ratio for each event

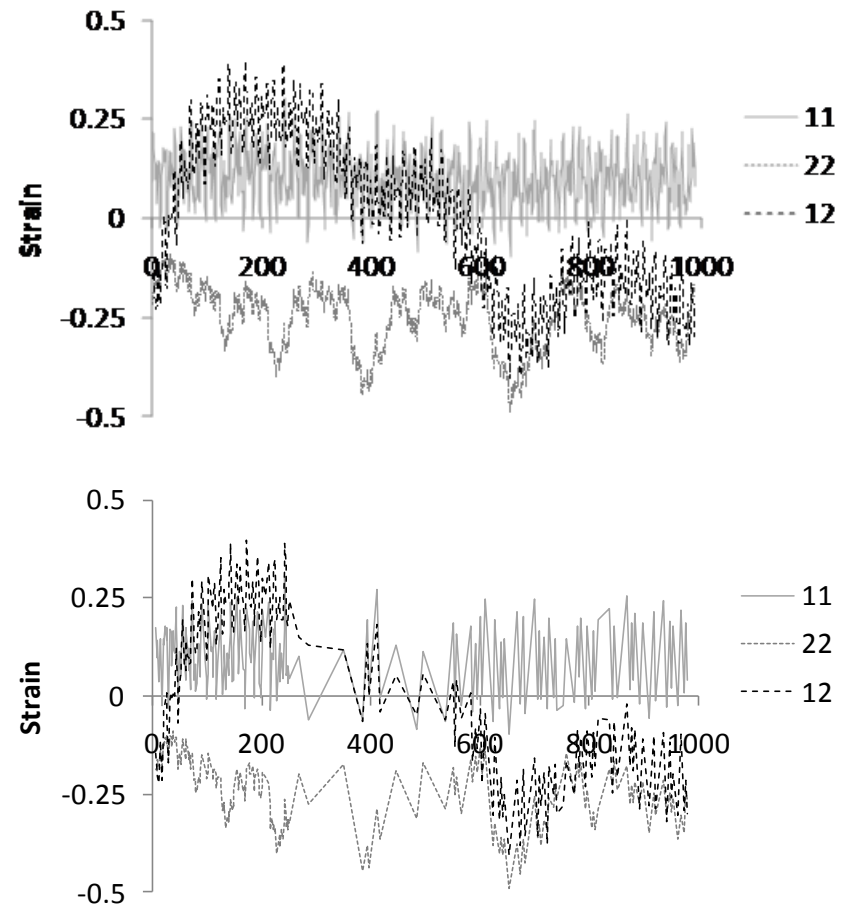
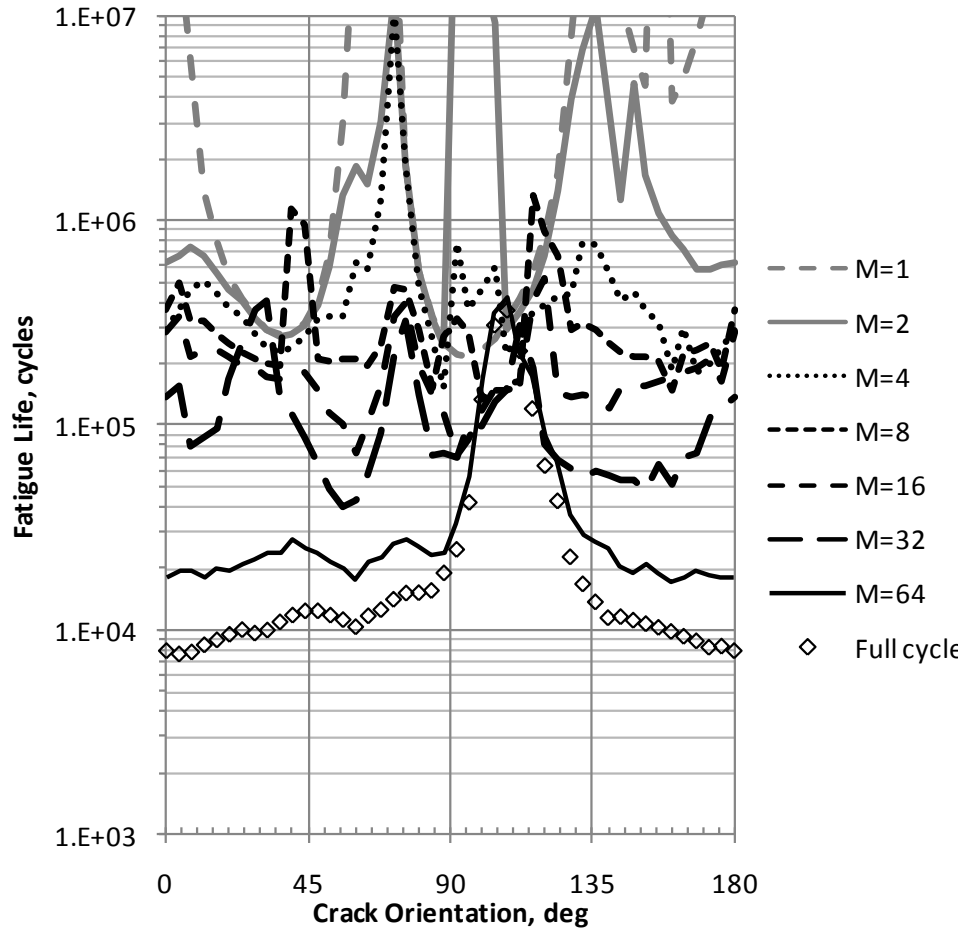


Damage Rate, by event



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

Construction of Abbreviated Strain History



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.