Characterizing Rubber's Fatigue Design Envelope

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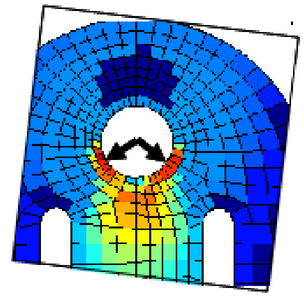
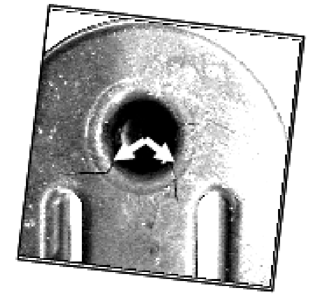
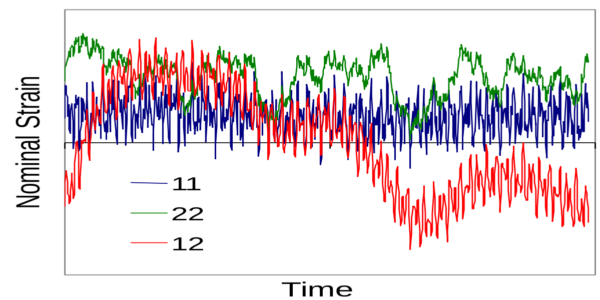
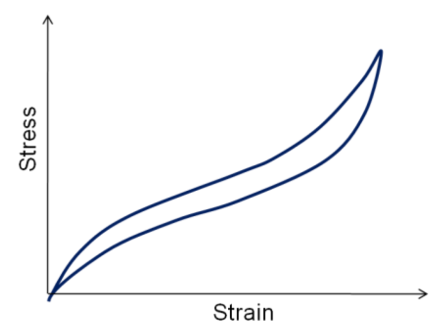
Overview of Issues Governing Fatigue Failure

- Geometry
  - Component characteristic dimensions
  - Stress-concentrating features
  - Strain-displacement and stress-load relationship(s)
- Duty Cycle
  - Static pre-load
  - Dynamic load (constant amplitude)
  - Loading spectrum (variable amplitude)
  - Cracks open or closed?
  - Stress vs. strain control
- Material
  - Stress-strain and strength properties
  - Crack growth properties
  - Strain crystallization
  - Initial damage state
  - Self-heating









Purpose

- Characterize the material in a way that
  - Indicates likely fatigue performance in actual service.
  - Reveals performance sensitivities to design options and governing parameters.
  - Shows bounds of available operating space.
  - Feeds simulation-based damage analysis
  - Empowers well-founded material dev. decisions

Fatigue Measurement Challenges

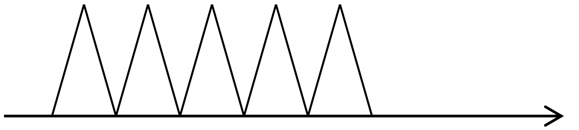
- Duration
  - Tests consume time on expensive equipment.
  - Upper limit on time budget is often much less than full service life
  - Test acceleration opportunity limited by self-heating
- Productivity
  - Observing a representative range of operating conditions
  - Acquiring a sufficient record of damage development for analysis
  - Minimizing number of specimens consumed
- Repeatability
  - Intrinsic variations in initial damage state amplified by strong sensitivity to damage state and to applied load
  - Observation limits in both space (smallest observable crack growth) and time (time limit)
- Risk
  - Measurement paradigm / uncontrolled modes (sideways crack growth)
  - Wasted time or specimen

Approach

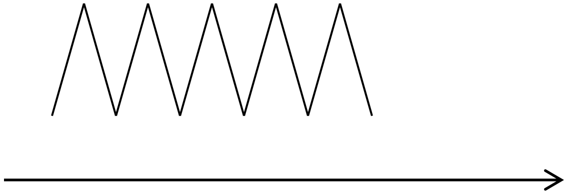
- Fracture mechanics experiments to characterize fundamental behavior governing crack development
- Numerical simulation to estimate and visualize consequences of measured behaviors

Test Inventory

- Fully-relaxing behavior
  - Static Tearing Procedure
  - 2 Hour Fatigue Crack Growth Procedure
  - 24 hour Fatigue Crack Growth Procedure
  - Crack nucleation Procedure
  - Flaw size Calculation
  - Strain-life curve Calculation



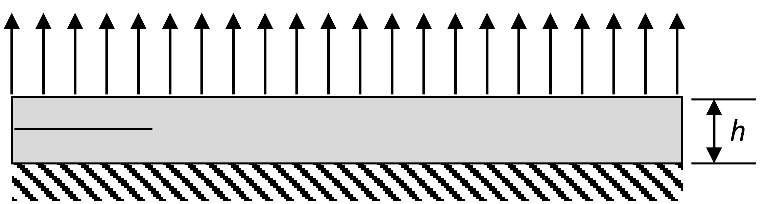
- Non-relaxing behavior
  - Crack Arrest Procedure
  - Haigh diagram Calculation



Test Specimens

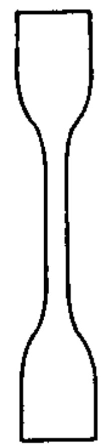
Fracture Mechanics Tests

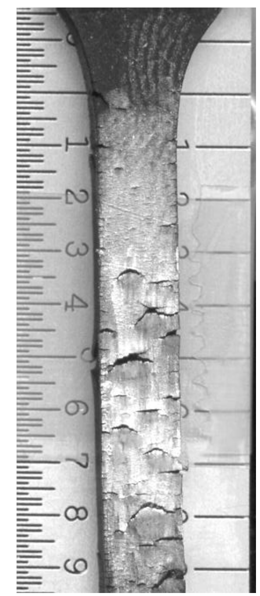
Courtesy Axel Products



Planar Tension (Pure Shear)

Nucleation Tests





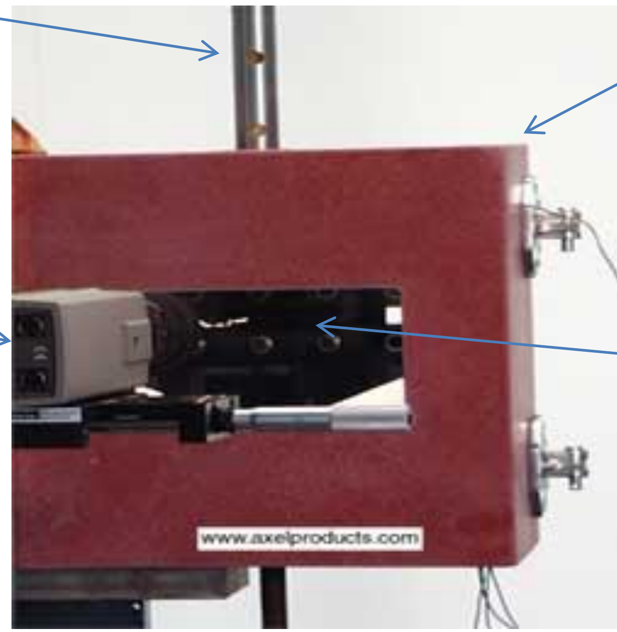
Simple Tension

Hardware

Servo-hydraulic actuator

Environmental chamber

CCD camera

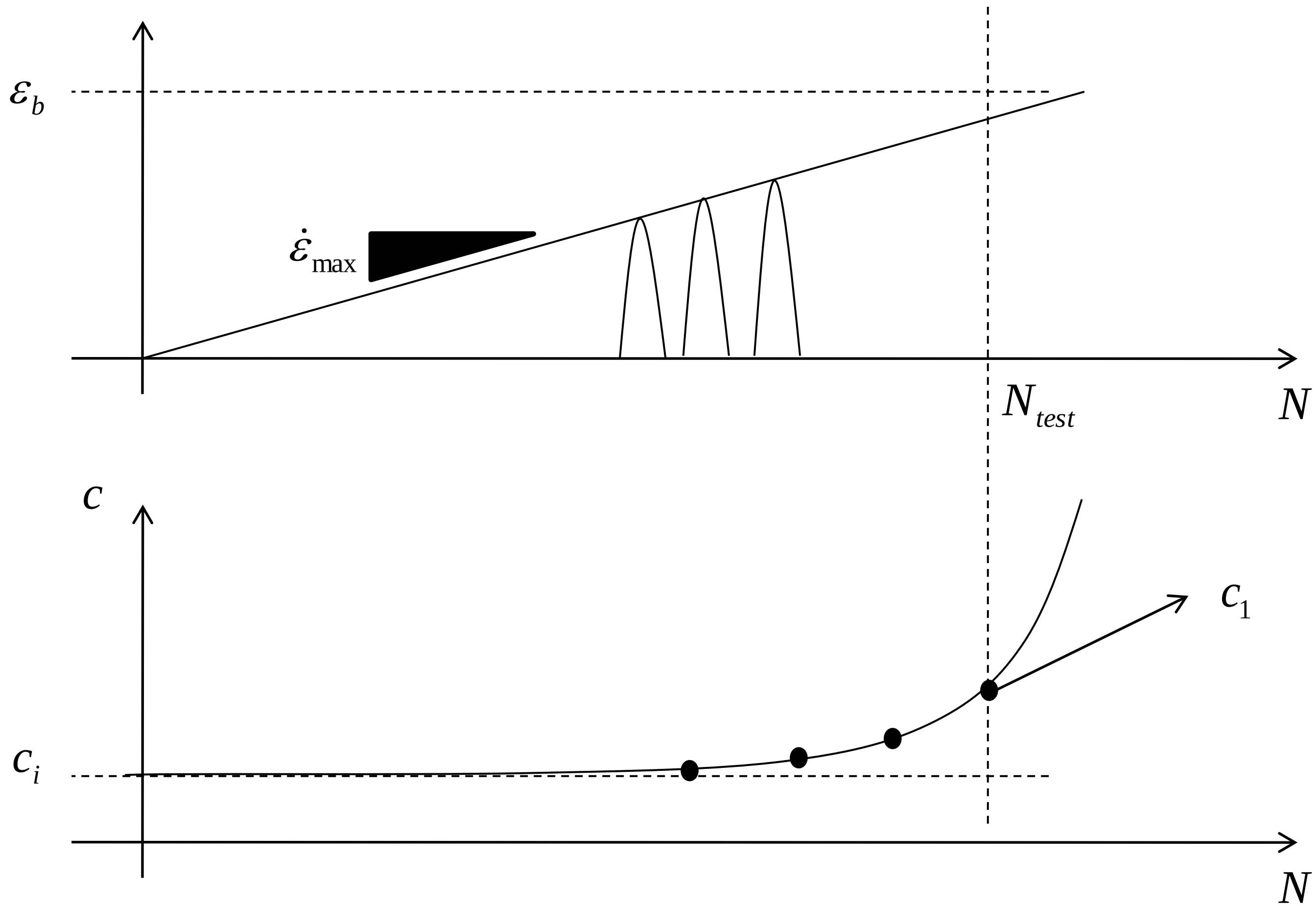


Edge-cracked specimen

Load cell

axel
physical testing services

Scheme for Fully Relaxing FCG Experiments



Expected Crack Growth

$$W = W(N)$$ Strain energy density

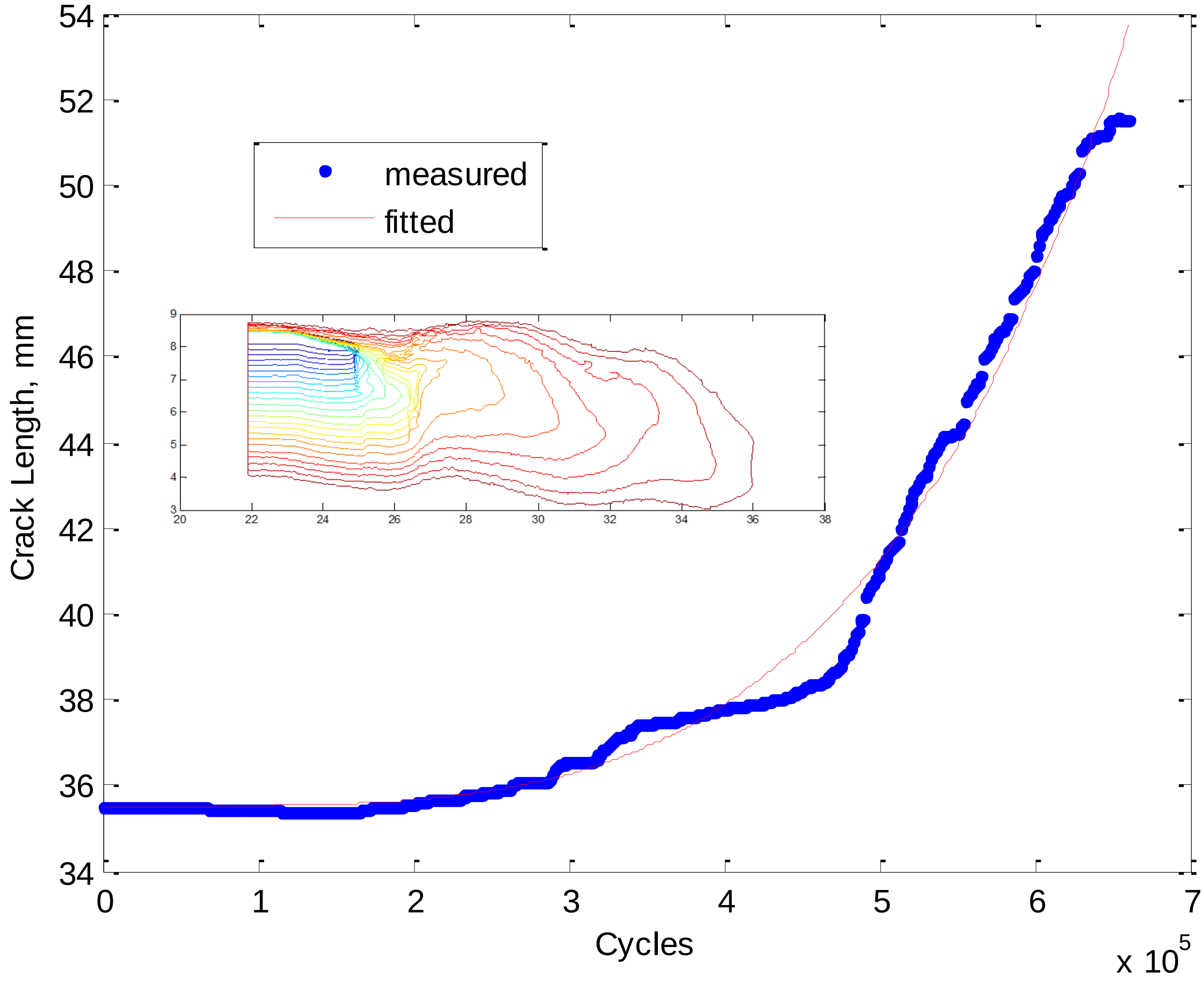
$$T = Wh$$ Energy release rate

$$r = AT^F$$ Crack growth rate law

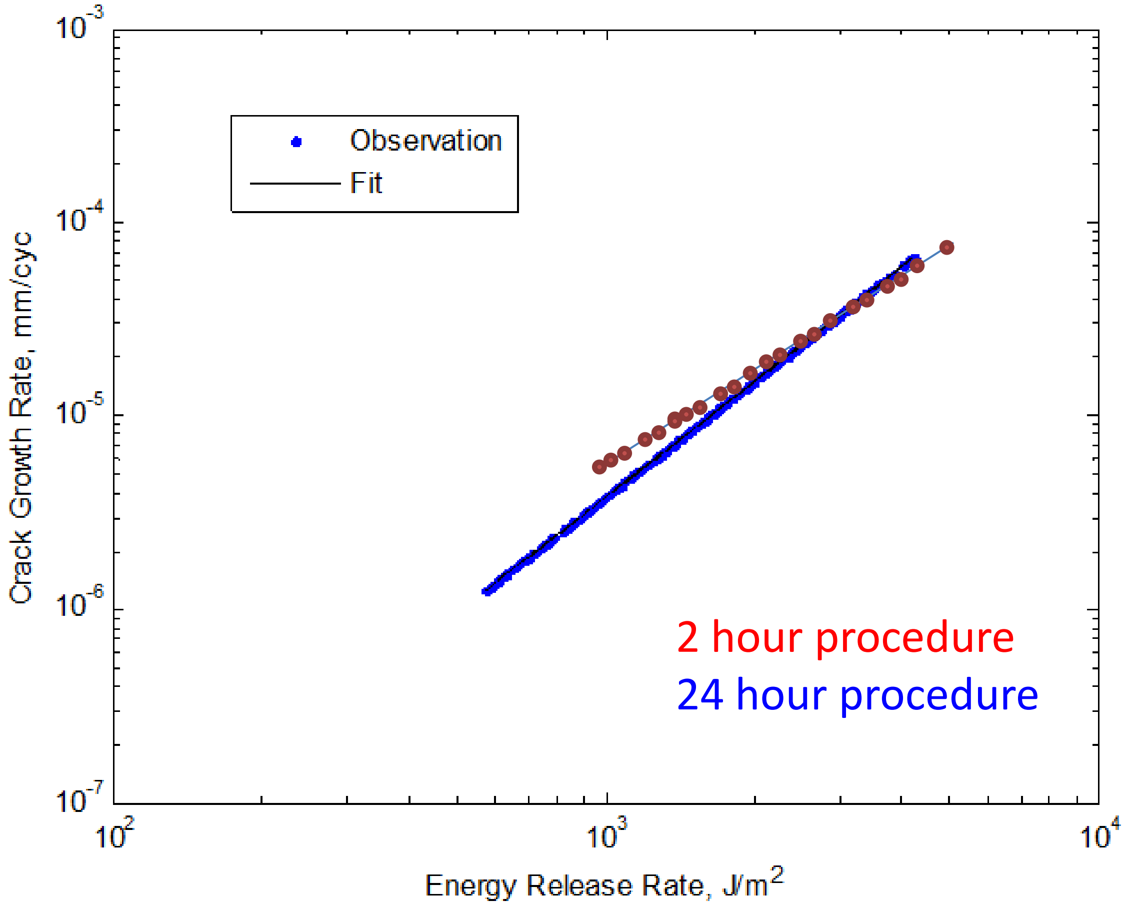
$$c - c_0 = \int_0^N A(Wh)^F dN = B\int_0^N W^F dN$$

Expected crack length history

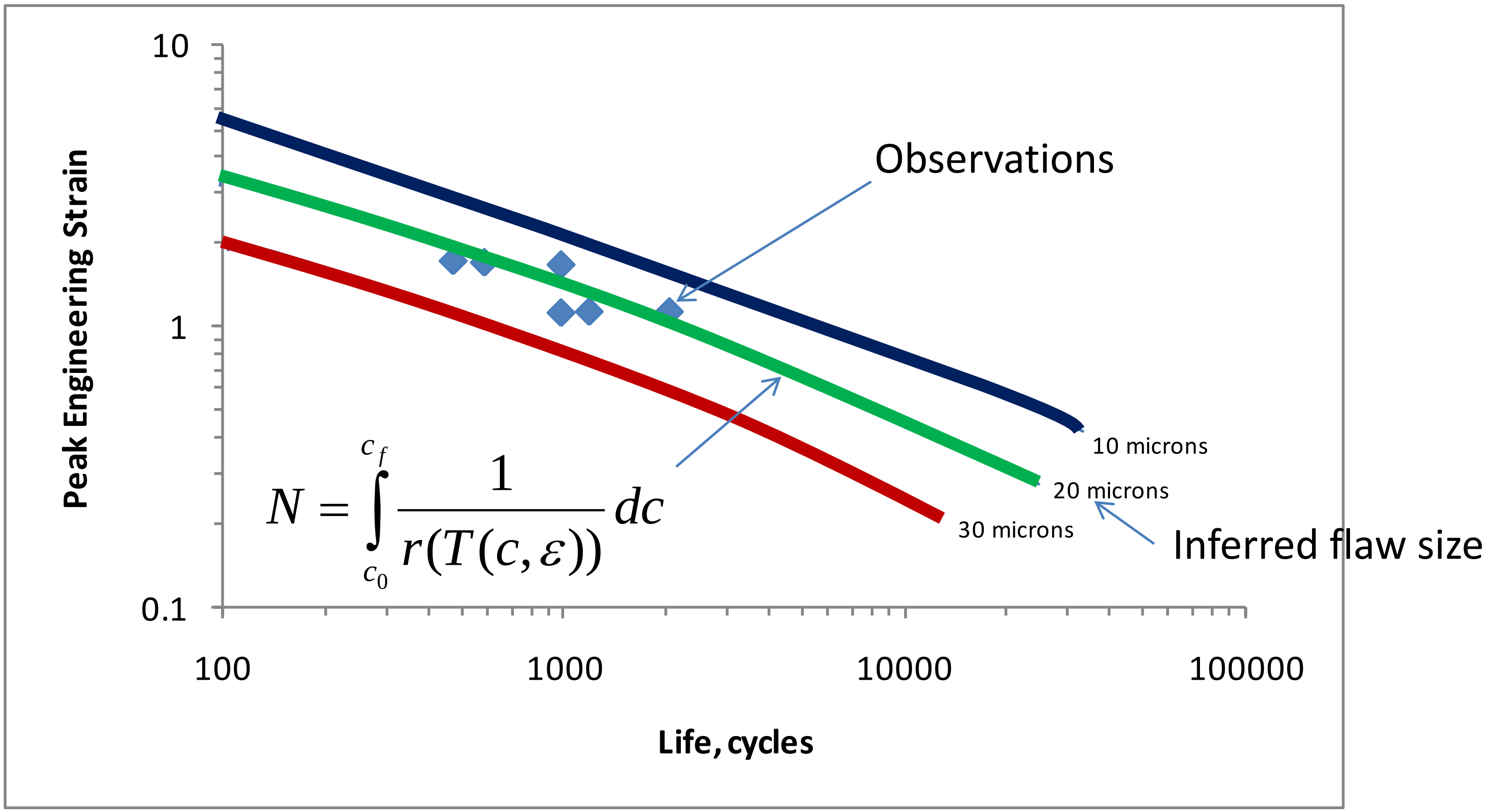
Observed and Fitted Crack Growth



Crack Growth Characteristic

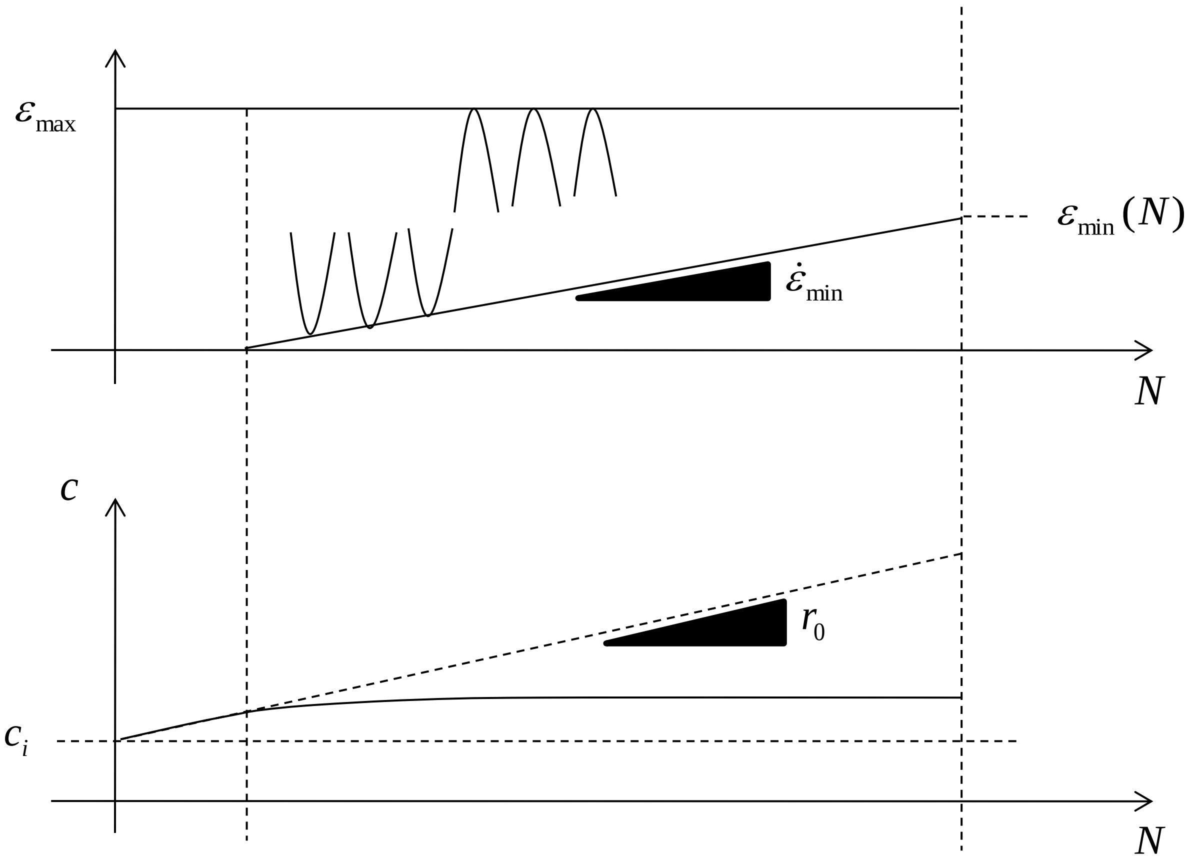


Crack Nucleation Tests

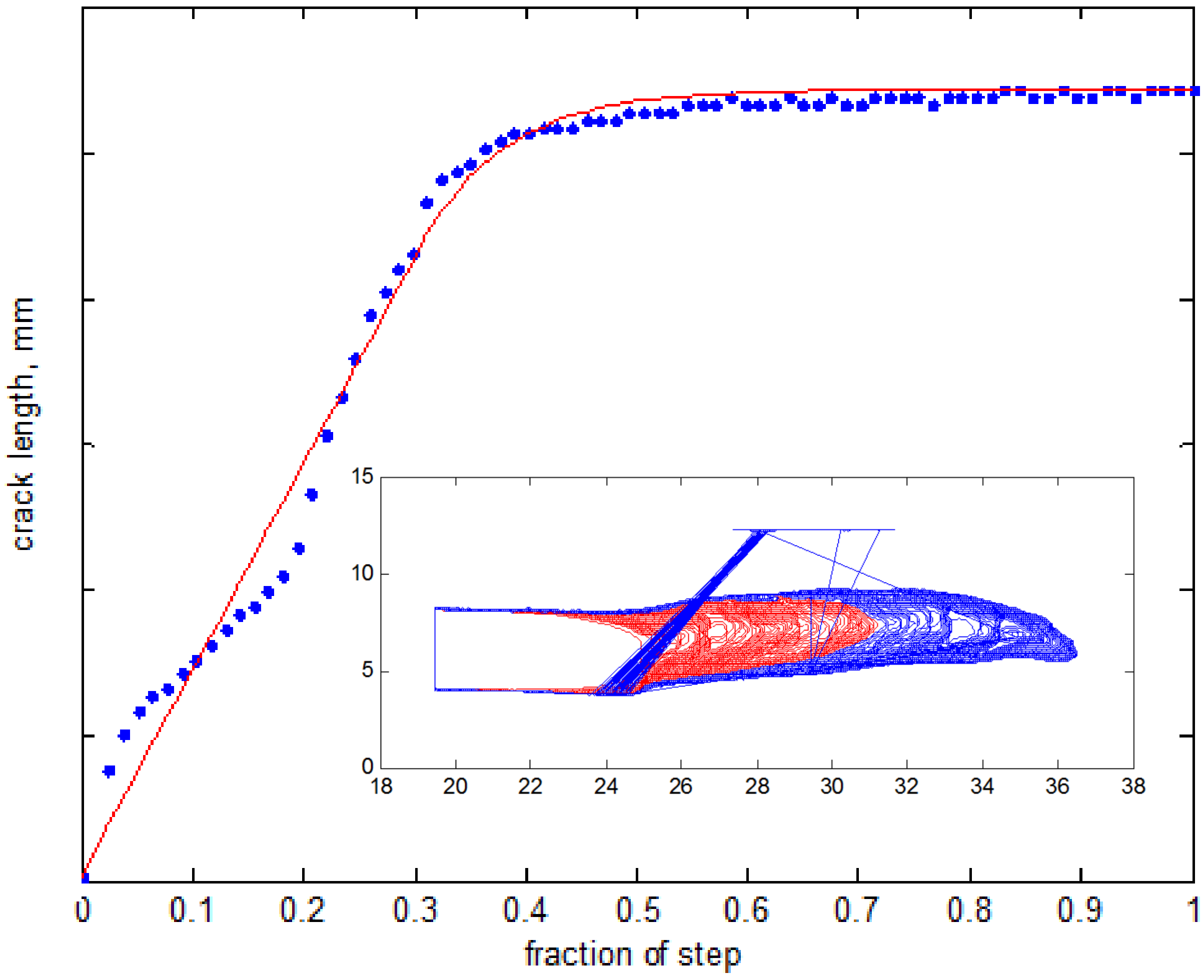


By combining a fracture mechanics test with a nucleation-style test, strain-life curves over a wide range of operating conditions can be constructed.

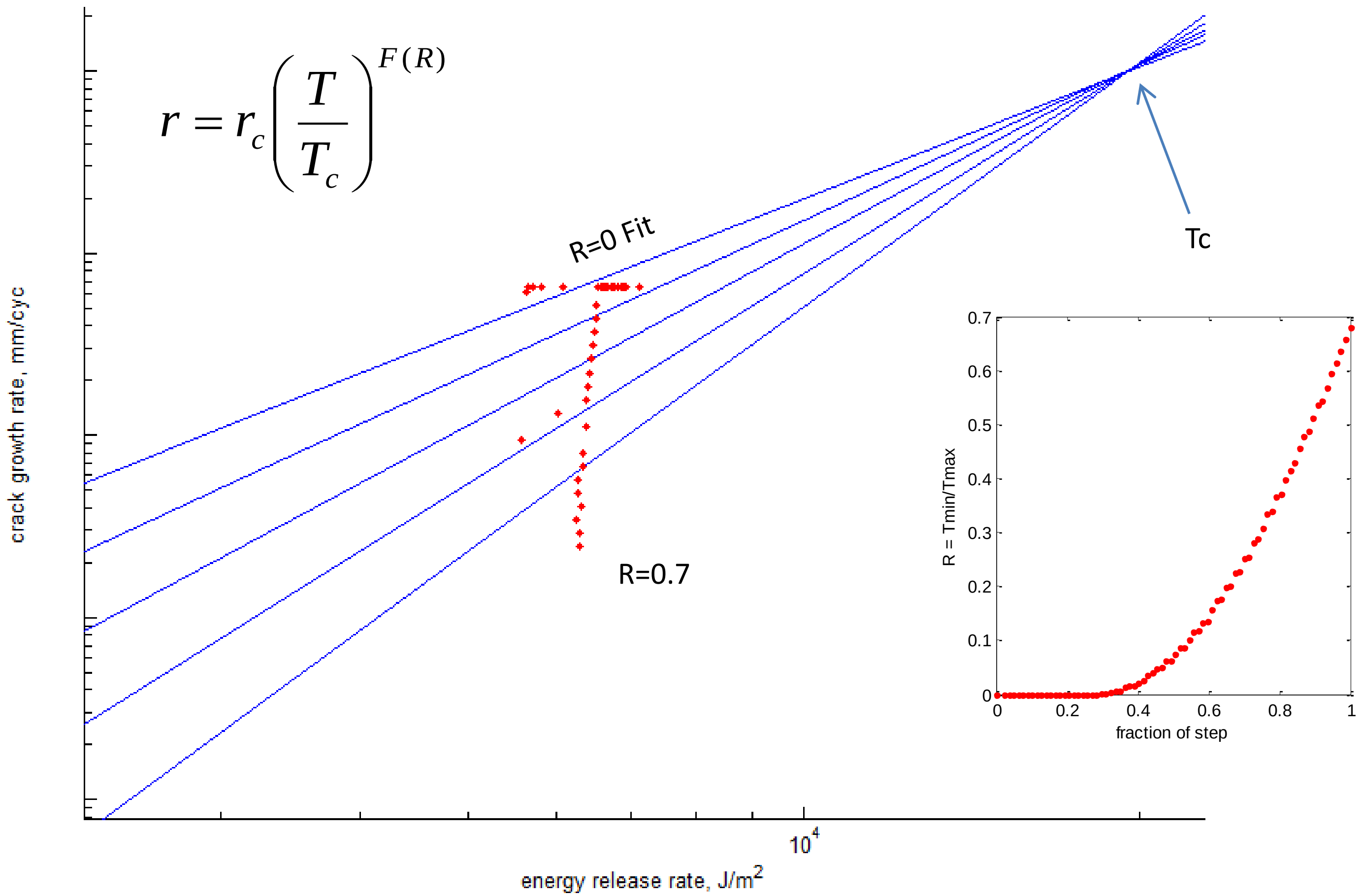
Crack Retardation Under Nonrelaxing Conditions



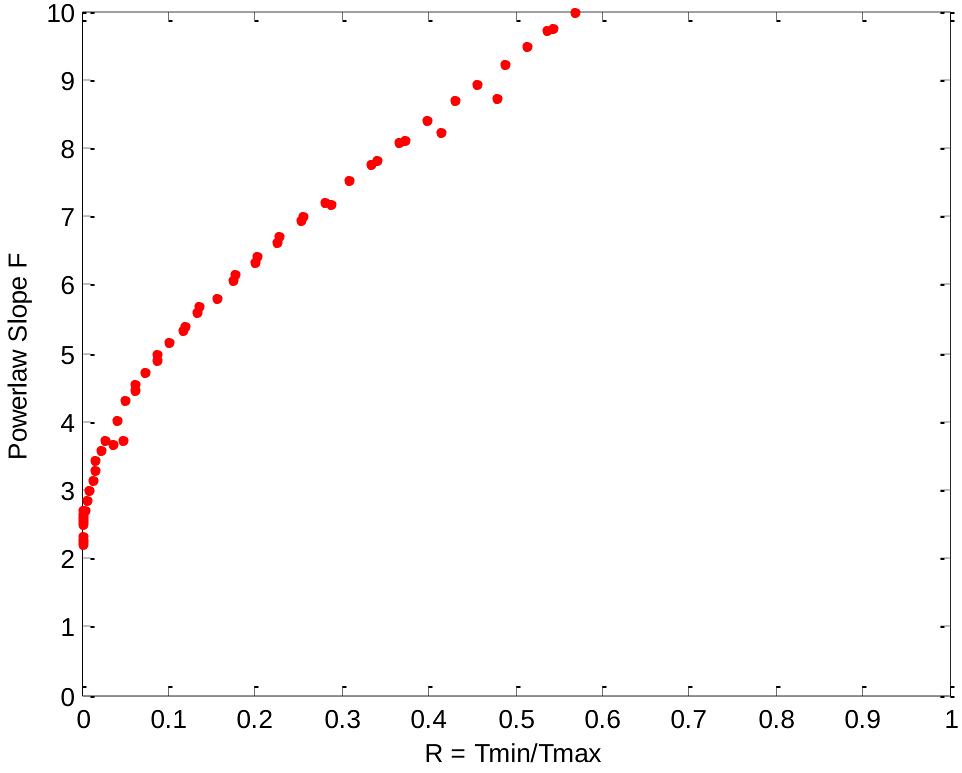
Typical Crack Arrest Observations



Fit of Strain-Crystallization Law to Arrest Data

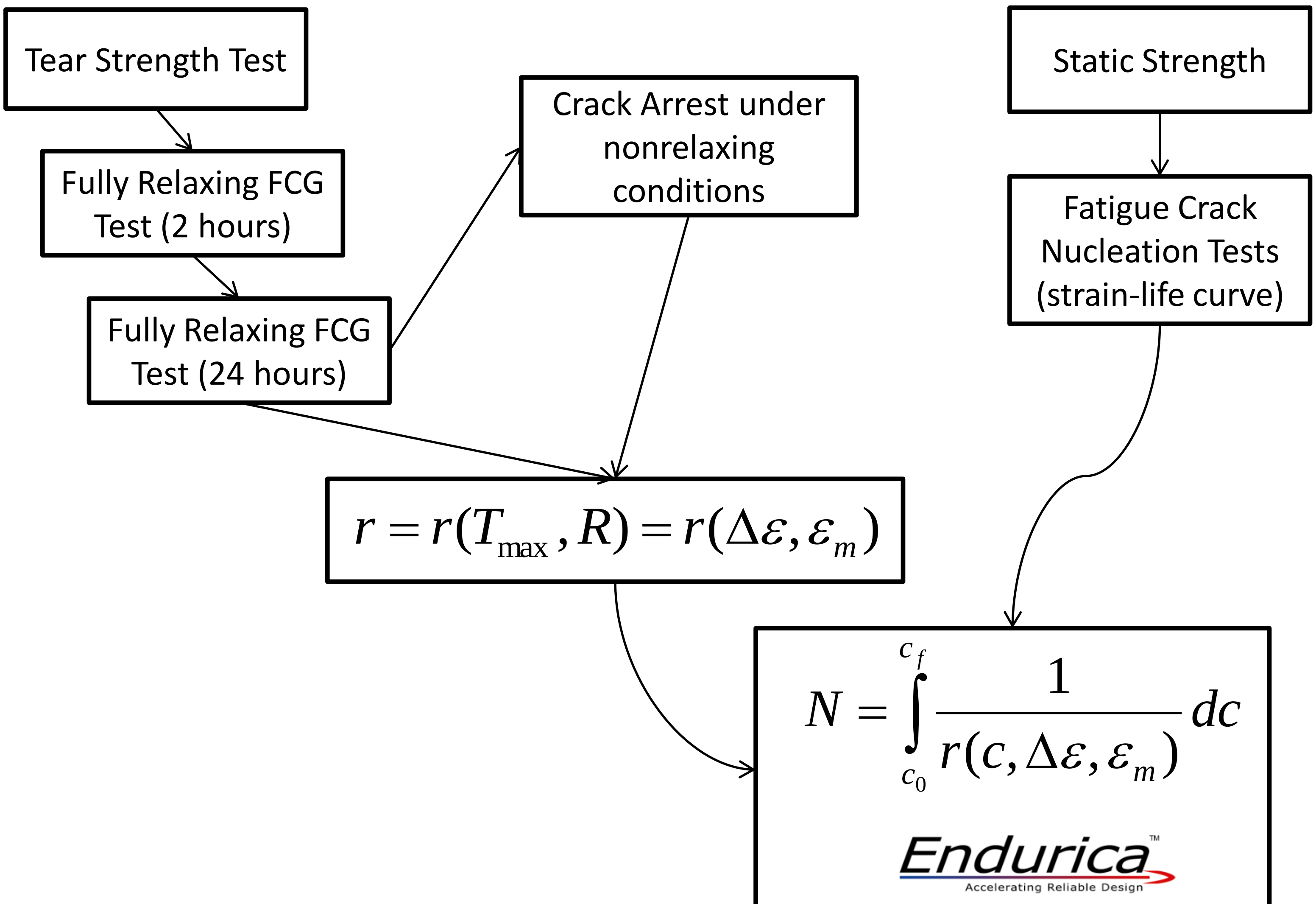


Crystallization Function

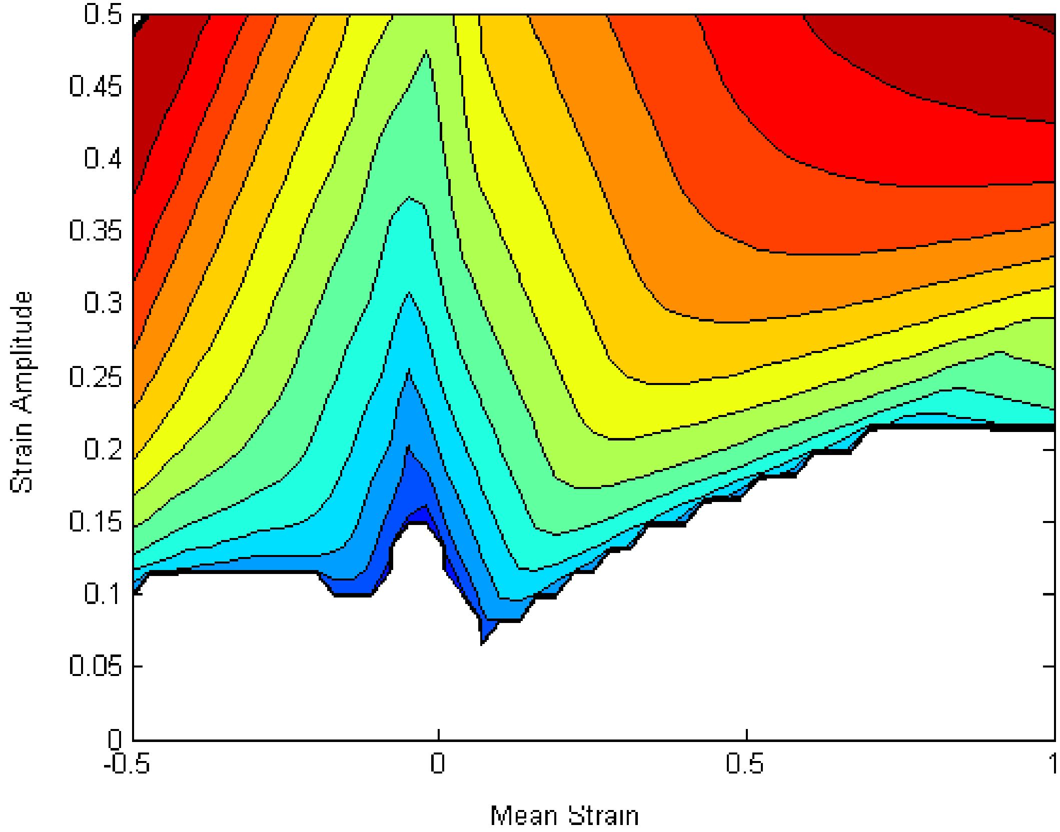


Directly shows the effect of nonrelaxing cycles on the powerlaw slope of the fatigue law

Computing the Design Envelope



Typical Design Envelope (ie Haigh Diagram)



NR

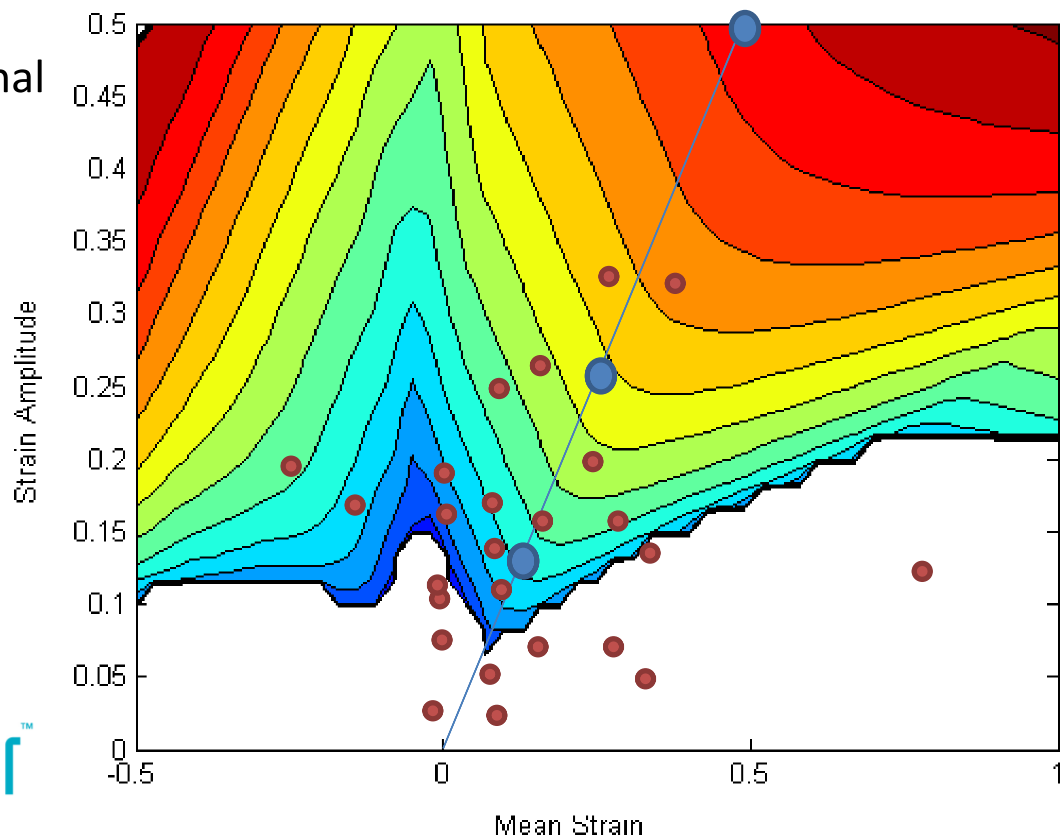
Simple tension / compression

The Haigh diagram shows, for a given fatigue life, the envelope of allowable combinations of mean strain and strain amplitude.

What use is the design envelope?

Conventional Lab test

In-Service Event



NR

Simple tension / compression

The Haigh diagram shows, for a given fatigue life, the envelope of allowable combinations of mean strain and strain amplitude.

Its very common that duty cycle contains few large events and many small events? Which actually are most significant to durability?

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Conclusions

- The design envelope
  - comprehensive perspective
  - necessary basis for evaluation of service condition effects
- Experimental and computational procedures have been developed to identify
  - Rubber’s fatigue design envelope
  - Parameters needed for damage simulation
- Procedures are optimized to provide maximum information and minimum risk for a given test time budget
- Useful for better-informed selection of materials for complex service environments, and simulation of components under complex duty cycles

Additional / Future Directions

- Self-heating
  - Materials characterization:
    - Hysteresis
    - Temperature effects on fatigue
  - Theory for estimating effects of complex dynamic strain cycles:
    - multiaxial
    - variable amplitude
  - Simulation for estimating self-heating in rubber components

Acknowledgement

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Abstract

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- For many applications, endurance under cyclic loading is an important and challenging design requirement. Ensuring adequate endurance requires knowledge of the limits of the material in the space of likely operating conditions, ie a design envelope. Although defining the design envelope for a given material can be laborious, it can also be rewarding, and there are at least a few published examples of such curves that have been developed for certain rubbers (the Haigh and Cadwell diagrams are examples). We have devised an efficient approach for characterizing rubber's fatigue design envelope. It is based on measurements of the fatigue crack growth rate law under both relaxing and nonrelaxing conditions. The measurement procedures are executed using the pure shear specimen, and they employ novel strain-ramping techniques that increase test reliability. After measuring the material's fatigue rate laws, we then numerically integrate them to produce a contour map showing how the fatigue life depends on duty cycle parameters such as strain amplitude, mean strain, and minimum strain.