Crack Growth Under Long-Term Static Loads: Characterizing Creep Crack Growth Behavior in Hydrogenated Nitrile

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W. V. Mars
Endurica LLC, Findlay, Ohio, USA
K. Miller
Axel Products, Inc., Ann Arbor, Michigan, USA
S. Ba & A. Kolyshkin
Schlumberger, Houston, Texas, USA

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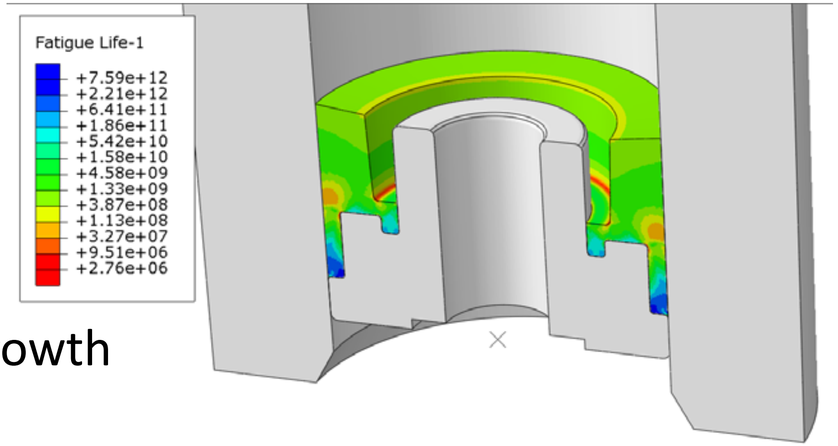
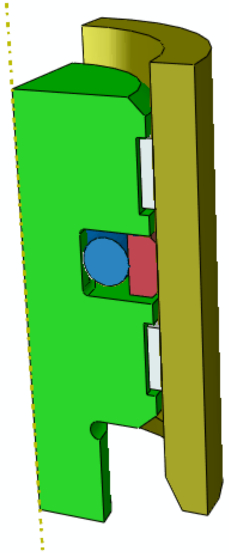
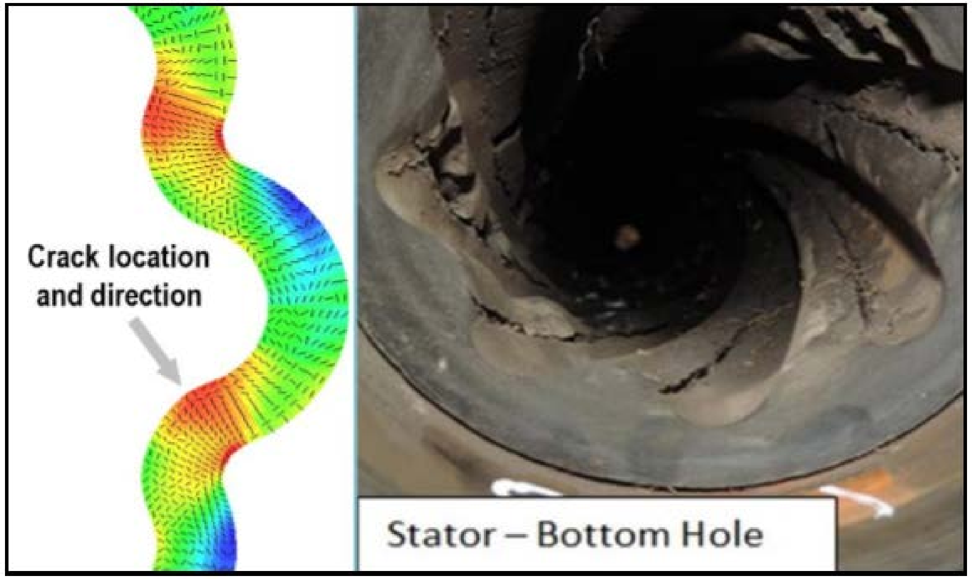
Context

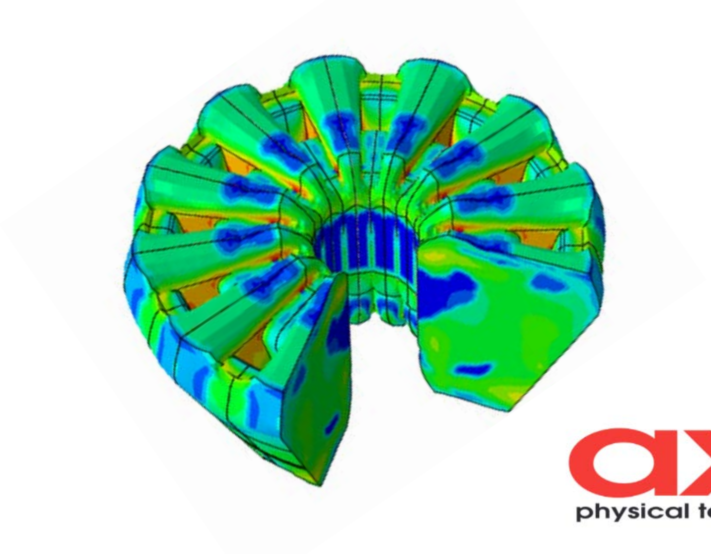
1. Applications w/ large static loads and long time periods
    - Seals, packers, mud motors etc.
    - Combined cycle/time dependent crack growth





2. Purpose
    - Obtain crack growth rate law parameters
    - Efficient and reliable execution





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Material Definition

Endurica CL™

fe-safe/Rubber™

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**MATERIAL

MAT=NBR
ELASTICITY_TYPE=NEOHOOKEAN
C10=1.157E6 ! PA
BULK_MODULUS=1000.0E6 !Pa
FATIGUE_TYPE=THOMAS
SIZEPRE=20E-6  !M
SIZEEOL=1E-3  !M
RC=0.40E-6   !(M/CYCLE)
TCRITICAL=3050 !J/m^2
F0=2.55
QUASISTATIC_TYPE=POWERLAW
RQS=1.26E-6 !m/s
TQS=2540 !J/m^2
FQS=3.69
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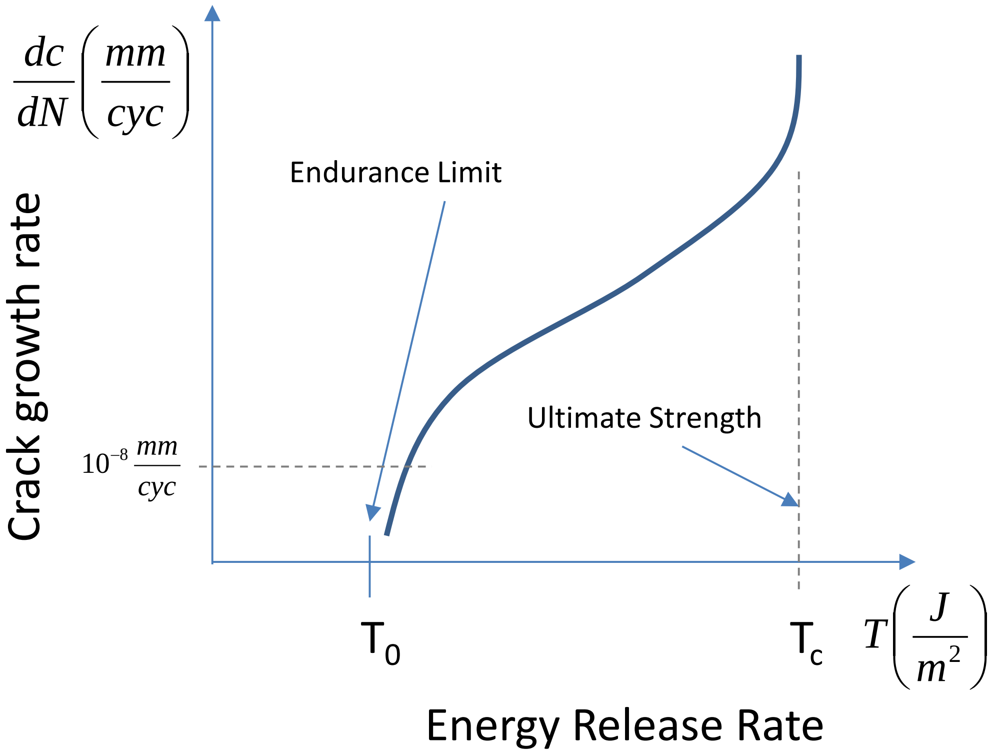

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Precedents

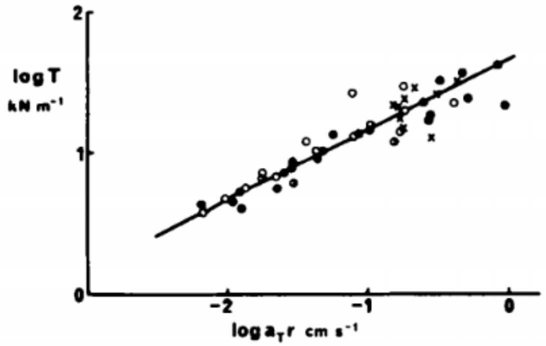

FIG. 6.—Composite curve for smooth tearing. ● NBR, ○ SBR, × NR. ◑ BR. The shift factor a_T is given in the text.

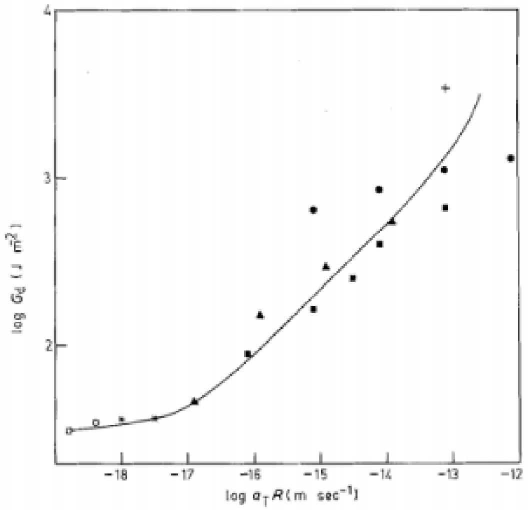

Figure 7 Detachment energy *Gd* against reduced rate Ra_T of crack propagation at T_g for neoprene rubber C(i). $\log a_T = [-17.4\,(T - T_g)]/[52 + (T - T_g)]$. (+) 0° C; (●) 25° C; (■) 45° C; (▲) 65° C; (×) 85° C; (∗) 105° C; (○) 125° C; (□) 150° C.

Kadir, A., & Thomas, A. G. (1981). Tear behavior of rubbers over a wide range of rates. *Rubber Chemistry and Technology*, *54*(1), 15-23.

Bhowmick, A. K. (1986). Tear strength of elastomers over a range of rates, temperatures and crosslinking: tearing energy spectra. *Journal of materials science*, *21*(11), 3927-3932.

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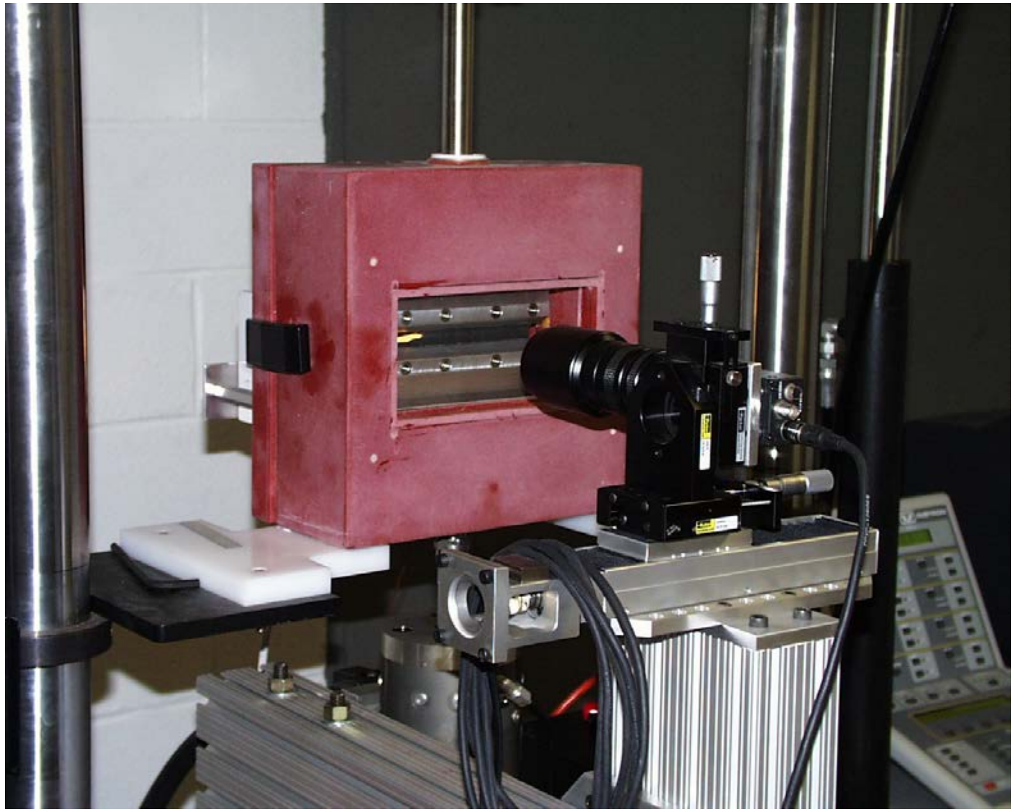
Combining Cycle- and Time- Dependent Crack Growth Rates

$$\frac{dc}{dN} = \left(\frac{dc}{dN}\right)_{cyclic} + \left(\frac{dc}{dt}\frac{dt}{dN}\right)_{steady}$$

G. J. Lake, P. B. Lindley, Journal of Applied Polymer Science, Vol. 8, pp. 455-466, 1964

Testing Hardware



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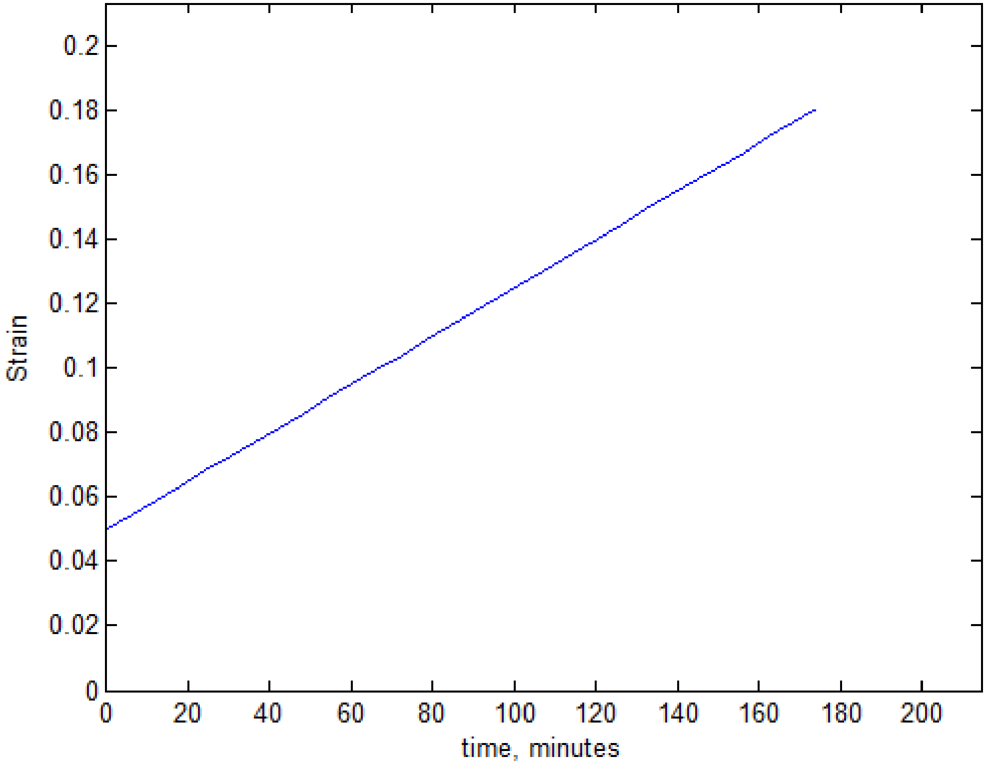
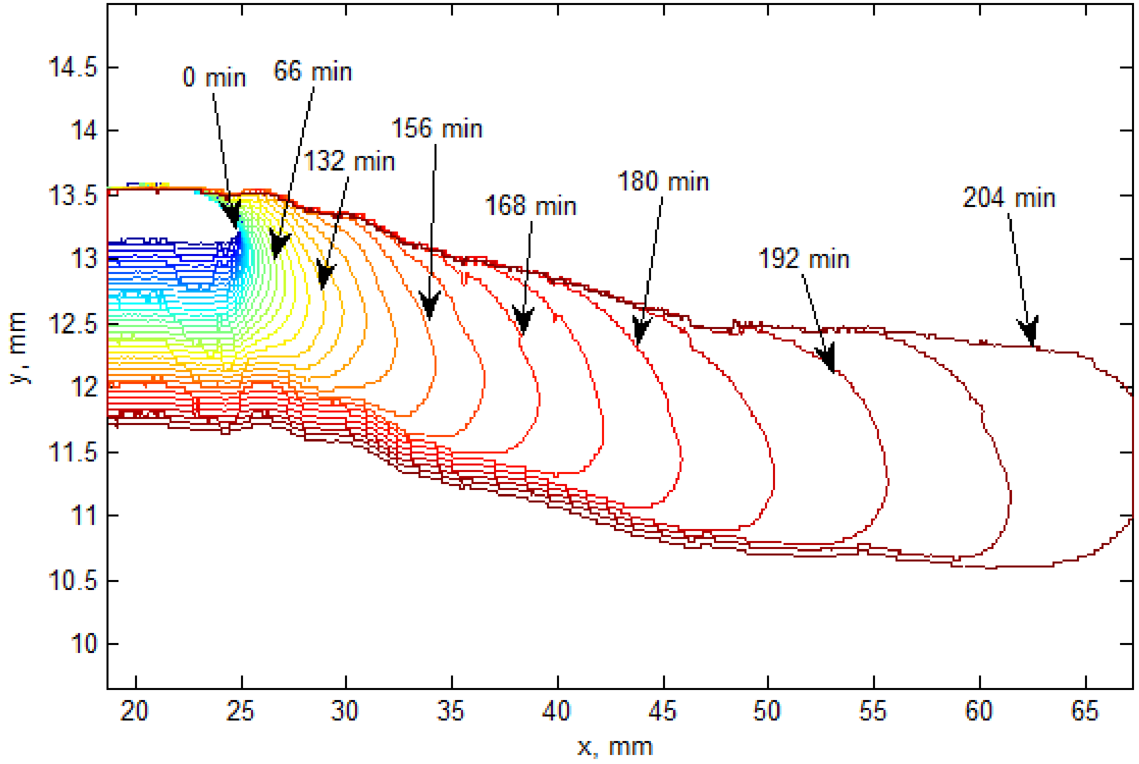
Quasistatic Strain Ramp Protocol

Courtesy Axel Products



Crack Tip Imaging and Measurement



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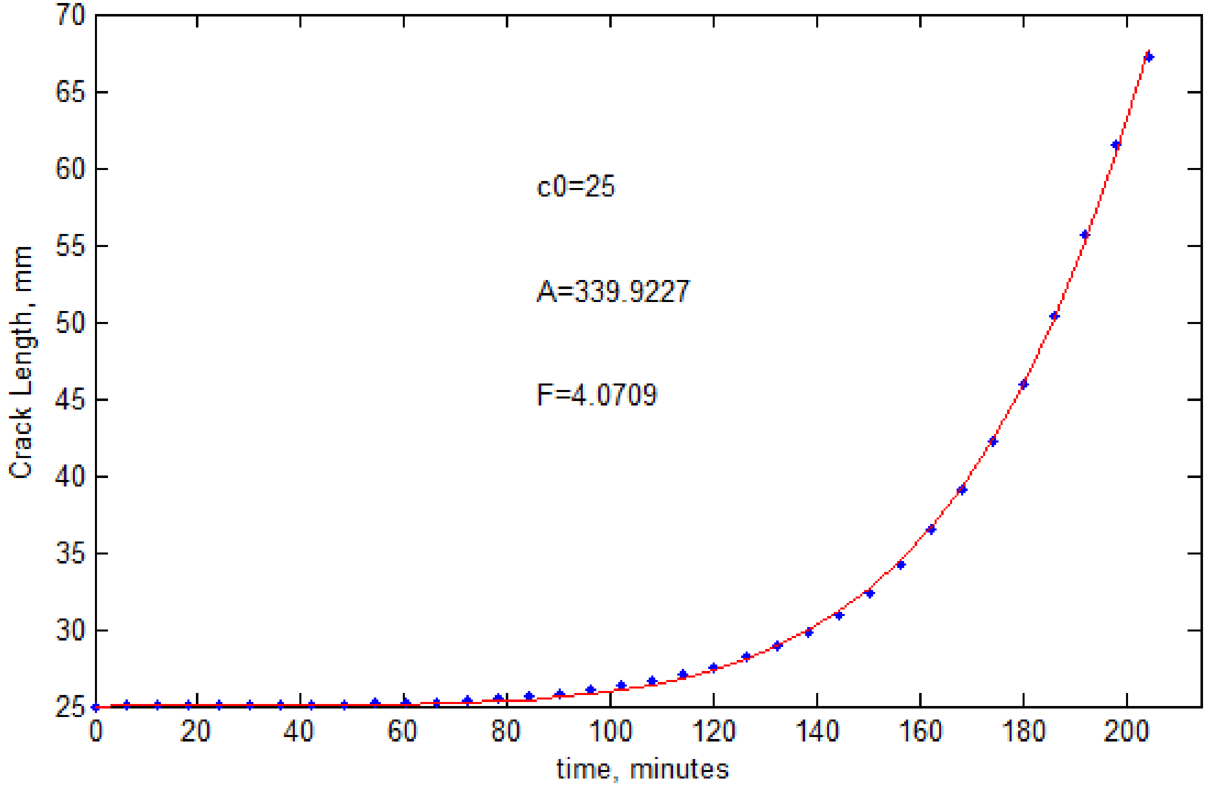
Crack Length history and curve fitting



$$\frac{dc}{dN} = r_q\left(\frac{Wh}{T_q}\right)^F$$

$$c = c_0 + r_q\left(\frac{h}{T_q}\right)^F \int_0^t W^{F_q}\,dt = c_0 + A\int_0^t W^{F_q}\,dt$$

$$E = \left(c(t) - \left[c_0 + A\int W^{F_q}\,dt\right]\right)^2$$

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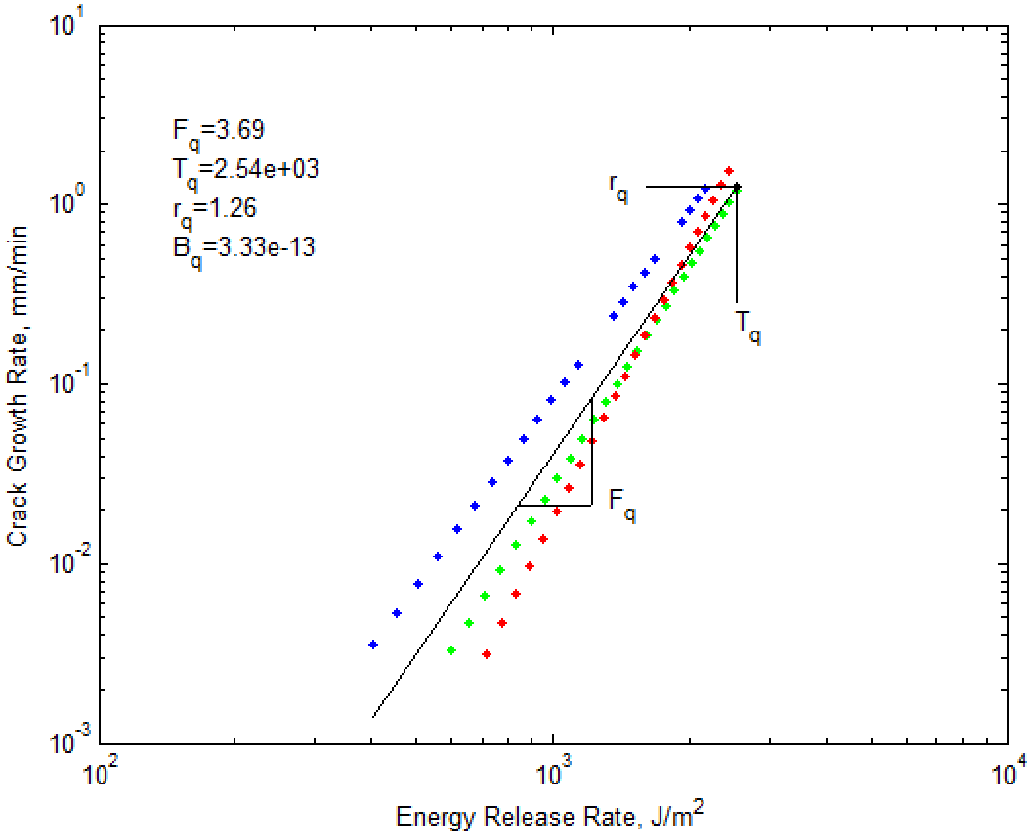
Creep Crack Growth Rate Law



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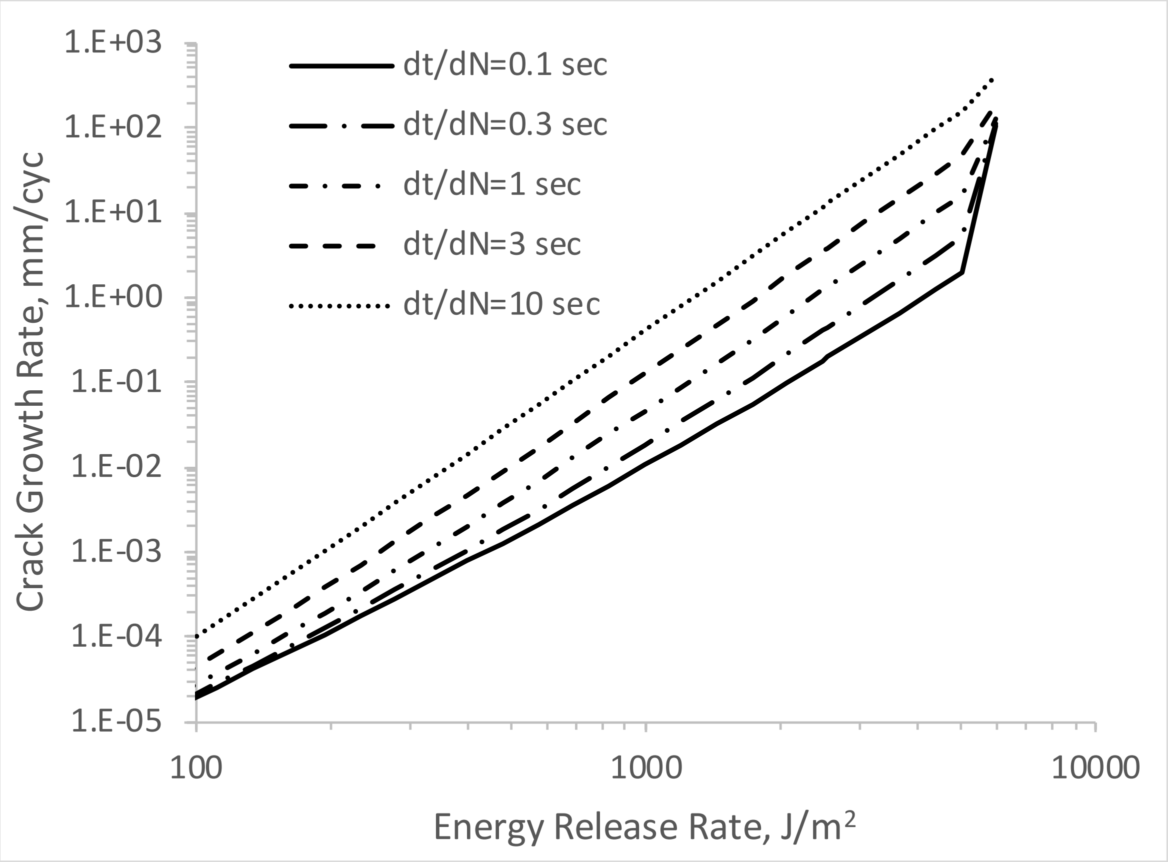
Time-dependent fatigue crack growth



	Fatigue	**Creep**
T	3.05 kJ/m2	2.54 kJ/m2
r	0.40 mm/cyc	1.26 mm/min
F	2.55	3.69

$$\frac{dc}{dN} = \left(\frac{dc}{dN}\right)_{cyclic} + \left(\frac{dc}{dt}\frac{dt}{dN}\right)_{steady}$$

$$\frac{dc}{dN} = r_c\left(\frac{T}{T_c}\right)^{F} + \frac{r_q}{\omega}\left(\frac{T_q}{T_q}\right)^{F_q}$$

Conclusion

- Developed procedure for observing time-dependent creep-crack growth rate law
- Useful when designing against loads that must be supported over a long period, or when analyzing mixed cyclic and time-dependent crack growth
- The slope of the creep-crack growth rate law may differ from the slope of the fatigue crack growth rate law. Indeed, in the case of filled HNBR, the creep slope was significantly higher than the fatigue slope

Characterization Toolbox for Durability

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

Nonrelaxing Module
Quantify Strain Crystallization, Min and Mean Strain Effects

Creep Module
Quantify Creep Crack Growth Rate Effects

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

Thermal Module
Quantify dissipative properties, thermal properties, temperature dependence

Cyclic Softening Module
Quantify Cyclic Softening Effects

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

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

Fatigue Property Mapping
Know Your Material

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