Testing and Analysis Methods for Rubber Durability

W. V. Mars

Endurica LLC

September 26, 2023

Ohio Rubber Group

About Endurica LLC

Jesse Suter
Development Engineer

Mark Bauman
Engineering Analyst

Abdullah Al Amin, Ph.D., Project Engineer

Will Mars, Ph.D., P.E.
Founder and President

Tom Ebbott, Ph.D.
Vice President

Joe Suter
Financial Manager

Pauline Glaza
Marketing Manager

Ethan Steiner, Sales Engineer

- Focus: simulating elastomers and durability
- 13 of the top 20 global rubber part suppliers use Endurica solutions

Common Design Intentions / Requirements for Durability

Infinite Life	No damage allowed	$T_0 \;\; c_0 \rightarrow \;\; S$
Safe Life	Design for Target Life	$r(T) \;\; c_0 \rightarrow \;\; N_f$
Damage Tolerant	Monitor | Inspect Predict Remaining Life	$r(T)\; c_0 \rightarrow \Delta N, \Delta\text{c}$

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September 24, 2021 11:09 AM

GM exec: Virtual design should be seen as opportunity

ANDREW SCHUNK

Rubber News Staff

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DETROIT—Zero crashes, zero emissions and zero congestion—these are just a few of the lofty goals that General Motors believes can be achieved as it considers an engineering and design future filled with virtuality, artificial intelligence and electric vehicles.

With its own stated mantra of the dissemination of tire knowledge, the Tire Society kicked off its 40th conference in typical technical fashion, offering a keynote address that addressed virtuality and its role in automotive and tire modeling.

"With a shared foundation of scientific knowledge, our ongoing mission is fulfilled best by the scientists and engineers who develop this technology," said Tire Society President Will Mars in his Aug. 30 virtual introduction.

Mars gave way to Mike Anderson, GM's executive director of global virtual design, development and validation, for his "Move to Virtual" keynote address. In it, Anderson discussed the savings, safety, regulatory environment and social acceptance of facing the technology in the coming years.

"We really amped up our move to virtual engineering starting in 2018, relying more and more on it to this day," he said, adding that the company already has reduced its tooling and physical prototyping costs for modeling by 66 percent, translating to $6.5 billion savings. "Our goal, our challenge, is to be 100-percent virtual in these efforts by 2025."

With virtual modeling, GM has reduced tooling and physical prototyping costs by 66 percent, translating to $6.5 billion savings. GM aims to have 100-percent virtual design capability by 2025.

- Mike Anderson
GM Executive Director of
Global Virtual Design, Development and Validation

Endurica
Get Durability Right

Fatigue Analysis Tools

Endurica CL™
Fatigue Analysis Software

CLassic “total” fatigue life calculation with post-process only workflow, for a single duty cycle.

Endurica DT™
Incremental Fatigue Solver

Incremental fatigue life calculation with co-simulation workflow for accumulating many duty cycles.

Endurica EIE™
Fast Loads Processing

Efficient Interpolation Engine for fast, nonlinear conversion of road load data to strain/stress history

Design Objectives and Analysis Approaches

	Endurica CL™ Fatigue Analysis Software	Endurica DT™ Incremental Fatigue Solver	Endurica EIE™ Fast Loads Processing
Infinite Life	New: Safety Factor		Nonlinear load mapping for rapid strain history calculation
Safe Life	Repeats	Repeats of a block cycle schedule	
Damage Tolerant		Incremental damage accrual, residual life	

companion
fatigue property comparator

40%

40% of product failure is attributed to poor materials selection

- Companion is a Fatigue Property Comparator
- Built for A to B comparisons
- Browser-based – works on both desktop and mobile
- Built on the Endurica fatigue solver engine / Critical Plane Analysis
- Simplified User Interface focused on key material properties
- Start for free at companion.endurica.com!
- Get advanced features with a subscription

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Material Testing Framework

Fatigue Property Mapping
Know Your Material

Basic mechanical behavior

Hyperelastic
Simple, planar, and equibiaxial tension, Mullins effect

Core Fatigue
Fully relaxing behavior from both nucleation and fracture mechanical perspectives

Common behavior

Thermal
Quantify dissipative properties, thermal properties, temperature dependence

Non-Relaxing
Quantify strain crystallization, min. and mean strain effects

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

Cyclic Softening
Quantify cyclic softening effects

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

Creep
Quantify creep crack growth rate effects

Reliability
Weibull statistics for strength and crack precursor size populations

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Materials Characterization

	Required / Basic			Advanced / Special Effects / Optional							
Infinite Life	Hyper elastic	Intrinsic Strength					Relia-bility				
Safe Life	Hyper elastic	Intrinsic Strength	Core Fatigue	Creep		Non-Relaxing	Relia-bility	Thermal Basic			
Damage Tolerant	Hyper elastic	Intrinsic Strength	Core Fatigue	Creep	Cyclic Soft-ening	Non-Relaxing	Relia-bility	Thermal Basic	Ageing Basic	Thermal Advanced	Ageing Advanced

Testing Instruments

Endurica is the exclusive distributor of these Coesfeld instruments in the Americas

Intrinsic Strength Analyser

- Measures cutting forces on an instrumented blade of controlled sharpness
- Indicates the threshold fracture mechanical strength of a polymer network (i.e. the mechanical fatigue threshold)
- Based on the Lake and Yeoh procedure

Tear and Fatigue Analyser

- Measures crack growth under dynamic loading cycles
- Produces the crack growth rate curve as a function of applied tearing energy
- Produces parameters for describing effects of strain-crystallization on crack growth
- Includes protocols for both fully relaxing (R=0) and nonrelaxing (R>0) conditions

Instrumented Chip and Cut Analyser

- Measures chip and cut resistance of rubber compounds under cyclic impact loadings
- Highly instrumented to enable control and measurement of forces and displacements during impact to mimic conditions experienced in demanding applications
- The instrument can be also be operated in full contact mode as a friction and wear measurement device

COESFELD MATERIALTEST

10

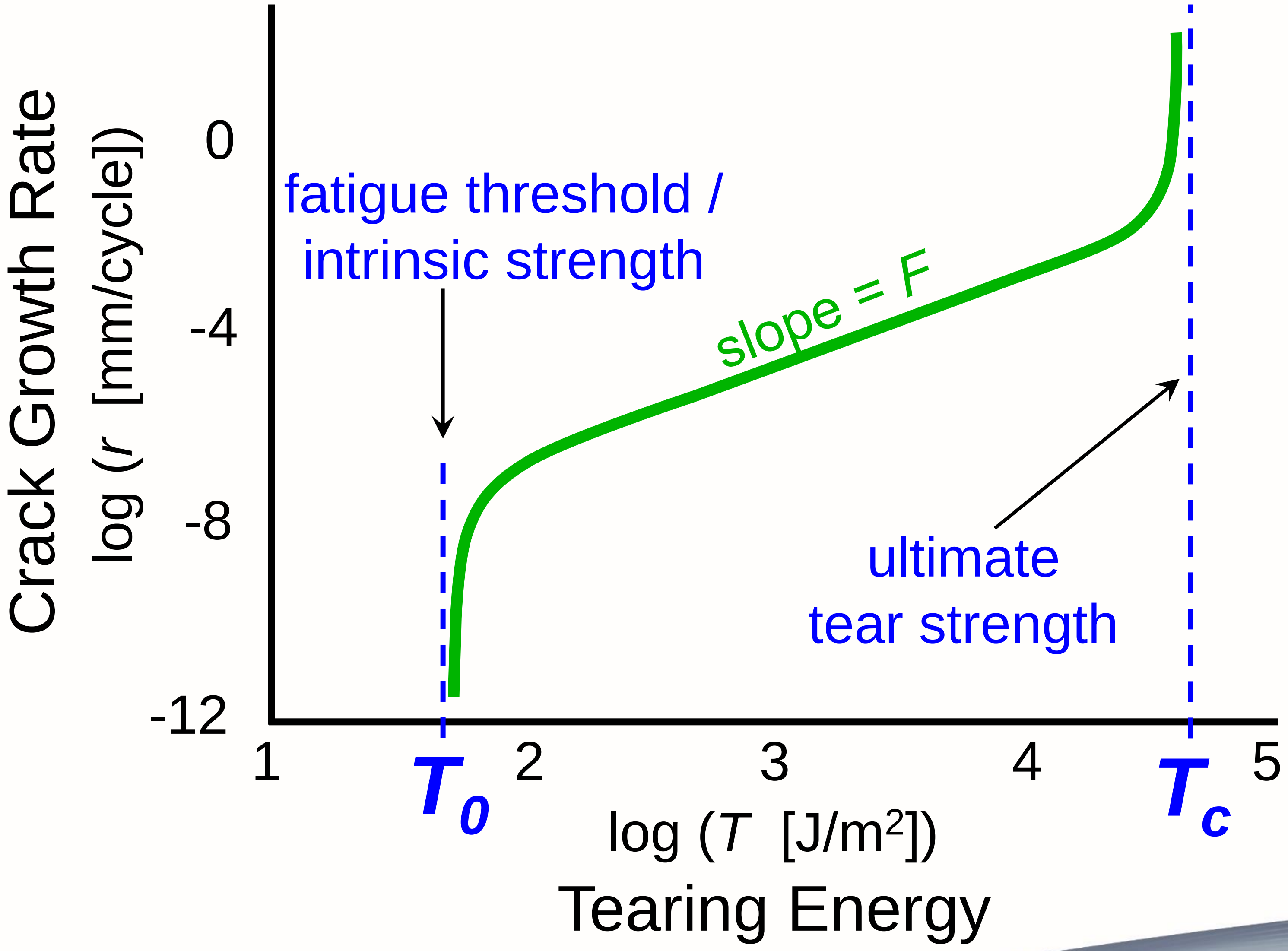
Approaches to Fatigue Testing

			ISA	TFA
				
Infinite Life	No damage allowed	$T_0 \;\; c_0 \rightarrow \;\; S$	Safety Factor	
Safe Life	Design for Target Life	$r(T) \;\; c_0 \rightarrow \;\; N_f$	Lake-Lindley rate law	Thomas, Paris, Lake Lindley Laws, Crystallization Law
Damage Tolerant	Monitor / Inspect / Predict Remaining Life	$r(T)\; c_0 \rightarrow \Delta N, \Delta c$		

Endurica Imperatives

- Accuracy
  - Nonlinear Effects -> Material models
  - Critical Plane Analysis – multiaxial, variable amplitude loading
  - Incremental Analysis – material property evolution
- Completeness
  - Support for infinite life, safe life and damage tolerant approaches
  - Support for Abaqus, Ansys, Marc and cosimulation
  - Support for full road loads
  - Support for tires: steady state and transient
  - Materials characterization infrastructure
- Scalability
  - Multithreading
  - Computational efficiency
  - Experimental efficiency

Upper and Lower Limits on Tearing Energy

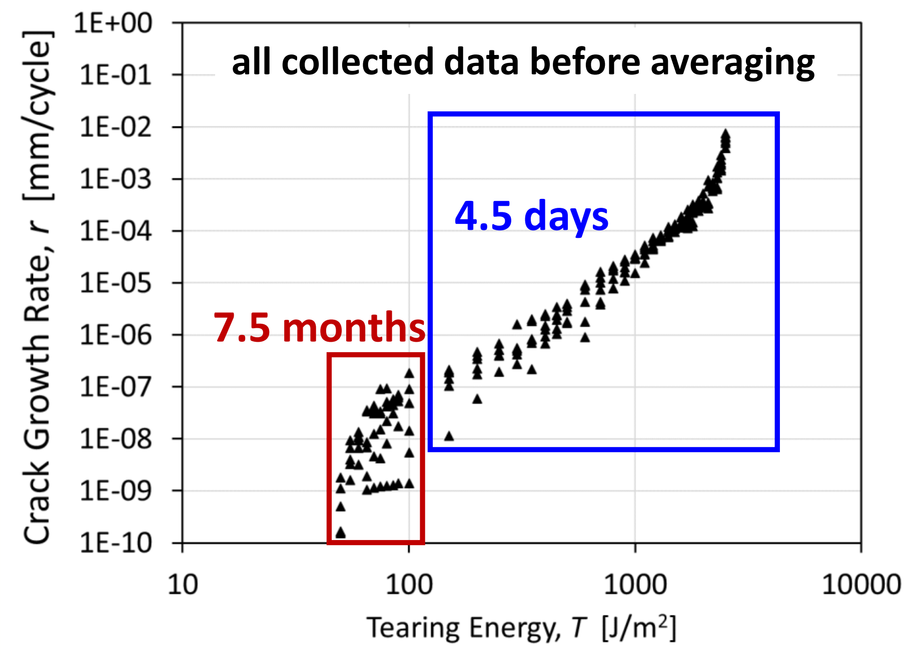


Intrinsic Strength Analyser

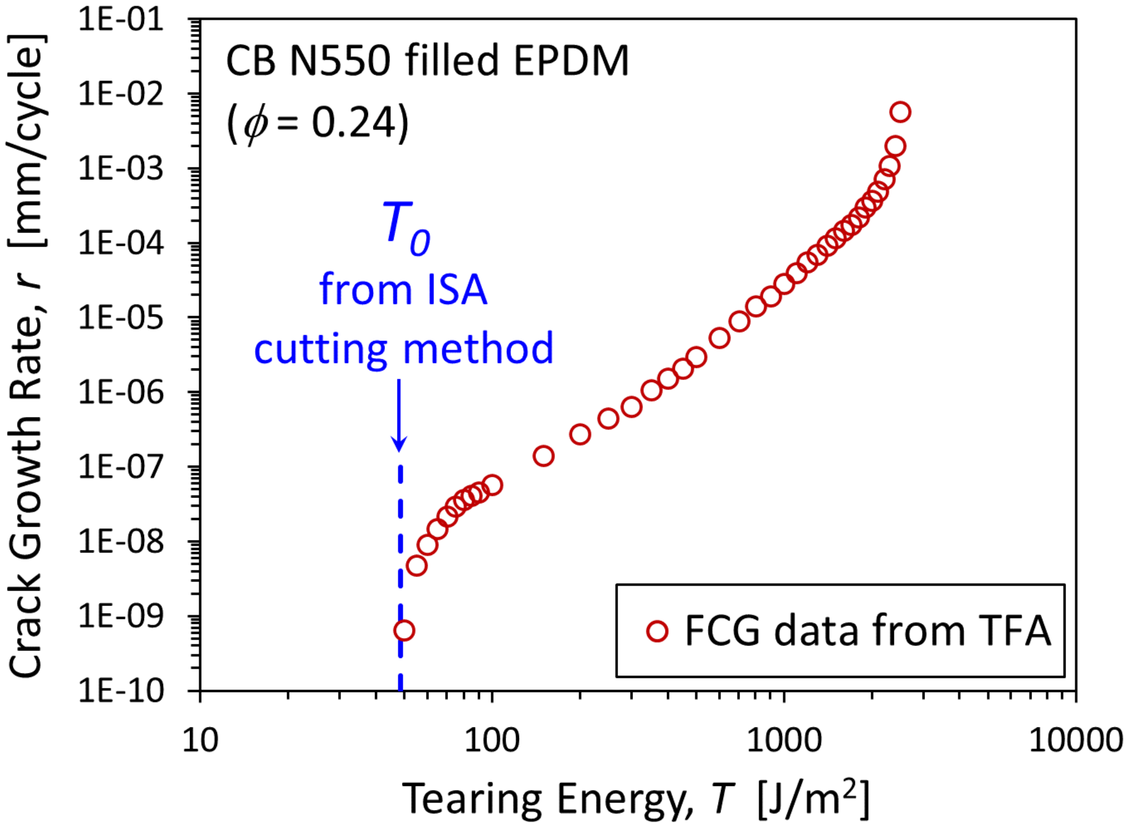
- Measures T_0 and T_c
- Rapid results (1 hour)
- Simple, conservative test
- Simple, conservative analysis

COESFELD MATERIALTEST

ISA vs. TFA



Stoček, R. (2021) Revision of Fatigue Crack Growth Characteristics of Rubber. Fatigue Crack Growth in Rubber Materials: Experiments and Modelling (eds. Heinrich, G., Stoček, R., Kipscholl, R.), Springer (chapter accepted for publication).



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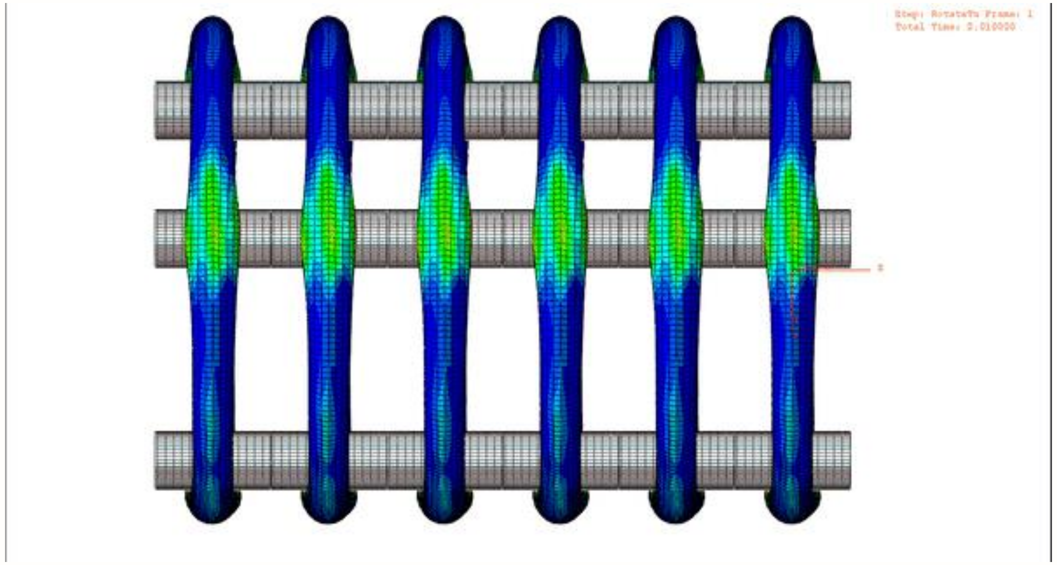
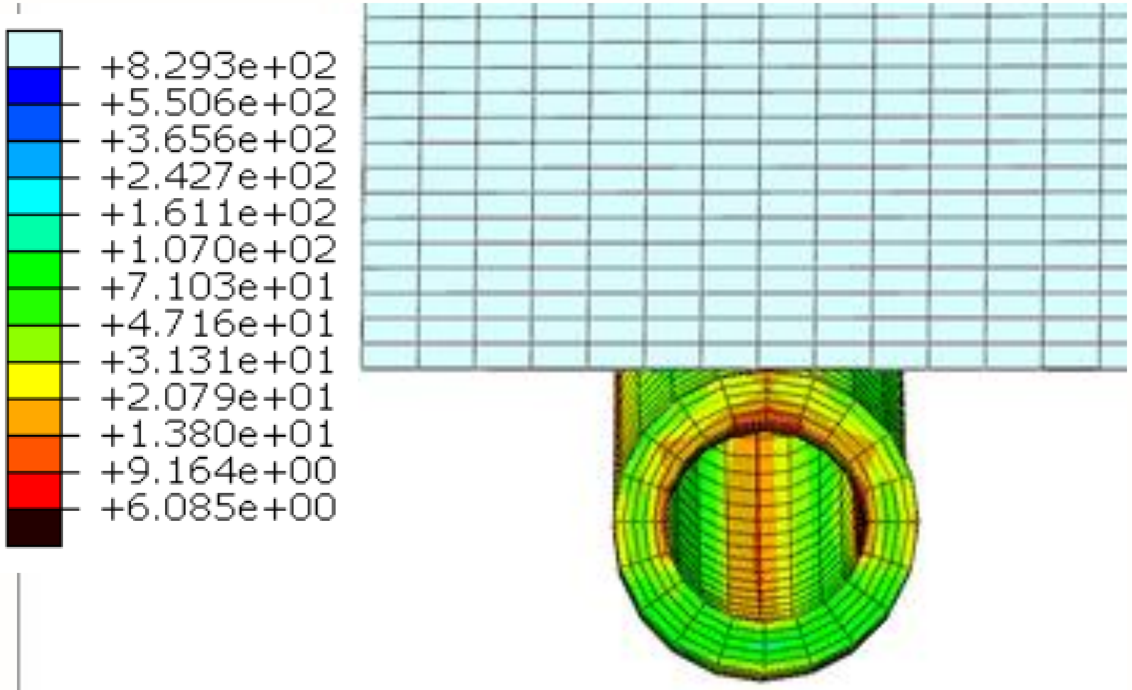
Fertilizer Squeeze Pump Safety Factor Analysis

Infinite Life Safety Factor Analysis





Endurica CL™
Fatigue Analysis Software

Hyper elastic

Intrinsic Strength

G = 0.68 MPa
C0 = 0.1 mm
T0 = 640 J/m^2

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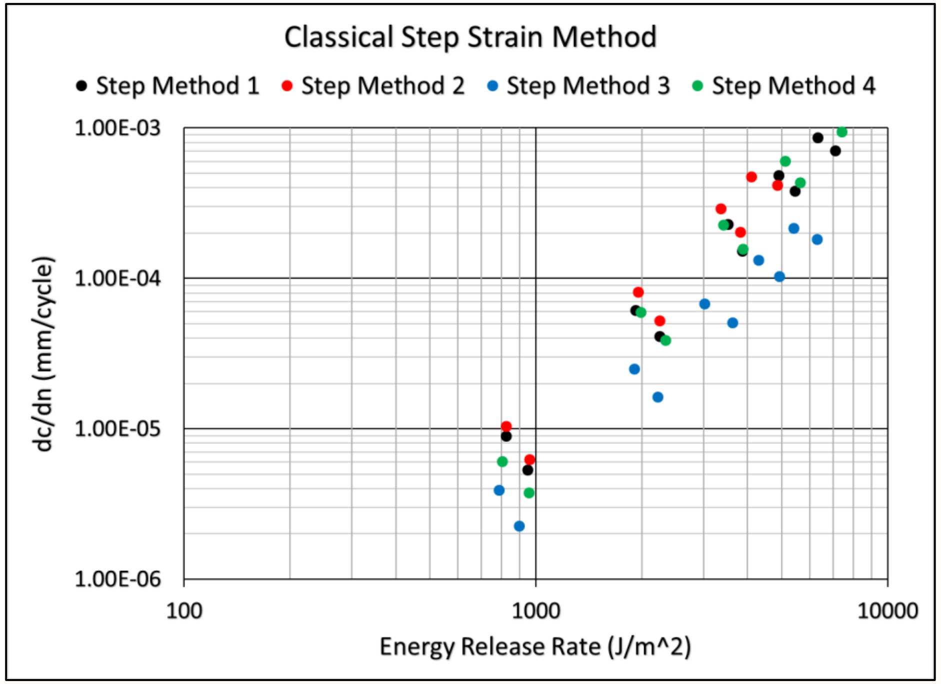
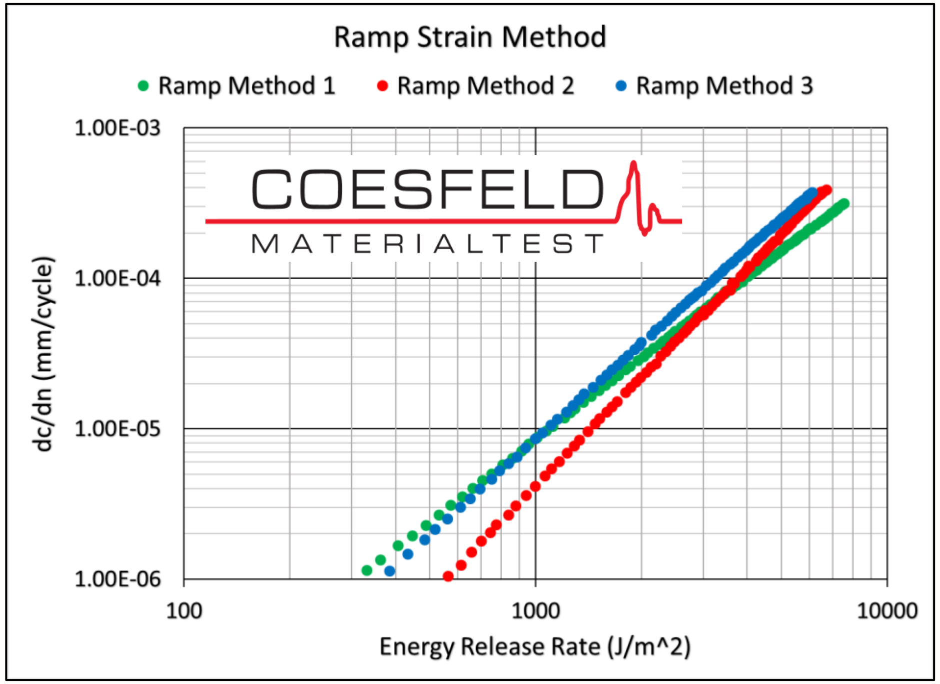
Fatigue Crack Growth Rate Measurement





	Step	Ramp
Fracture Strength T_c, J/m^2	18500	
Power-law Slope F_0	2.086	2.025
Reference growth rate r_c, mm/cyc	0.00442	0.00266
Standard Deviation s	0.262	0.108

Goossens, Joshua R., and William V. Mars. "Finitely scoped, high reliability fatigue crack growth measurements." *Rubber Chemistry and Technology* 91, no. 4 (2018): 644-650.

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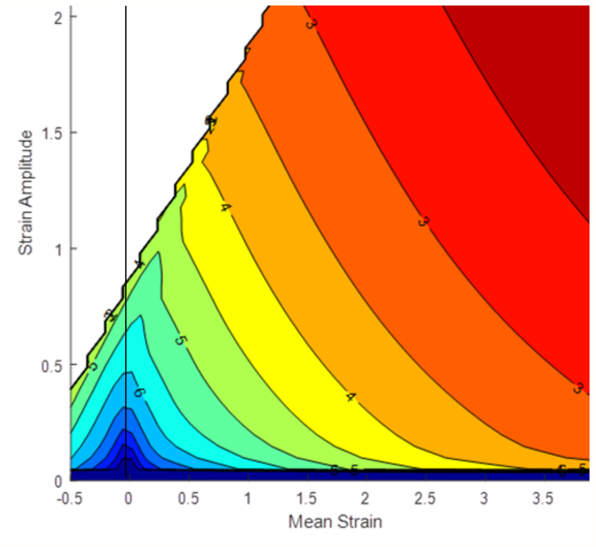
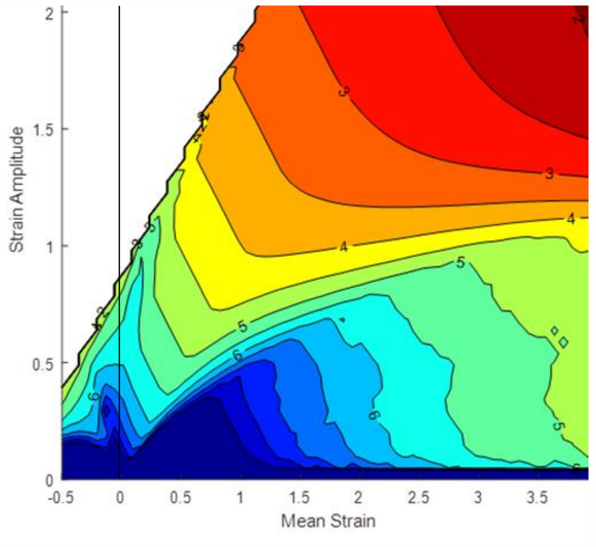
Strain Crystallization and Mean Strain Effects

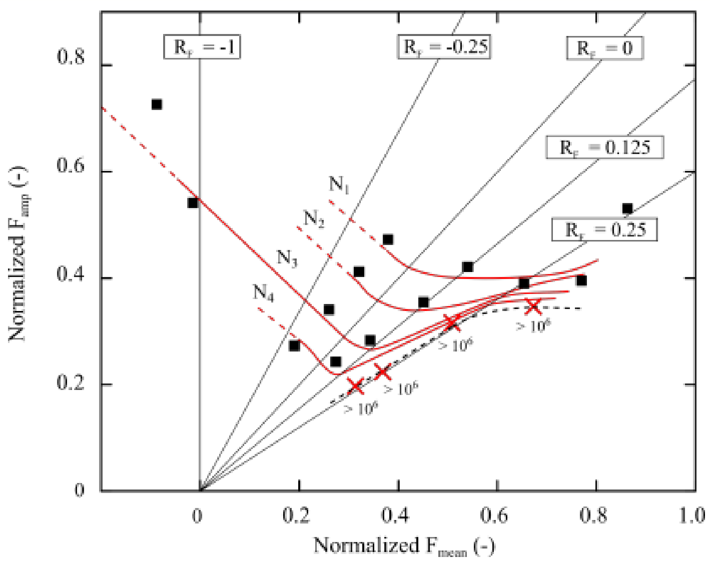
Non-Crystallizing (SBR)



Crystallizing (NR)



Crystallizing (NR)



Ruellan, Benoît, J-B. Le Cam, I. Jeanneau, F. Canévet, F. Mortier, and Eric Robin. "Fatigue of natural rubber under different temperatures." *International Journal of Fatigue* 124 (2019): 544-557.

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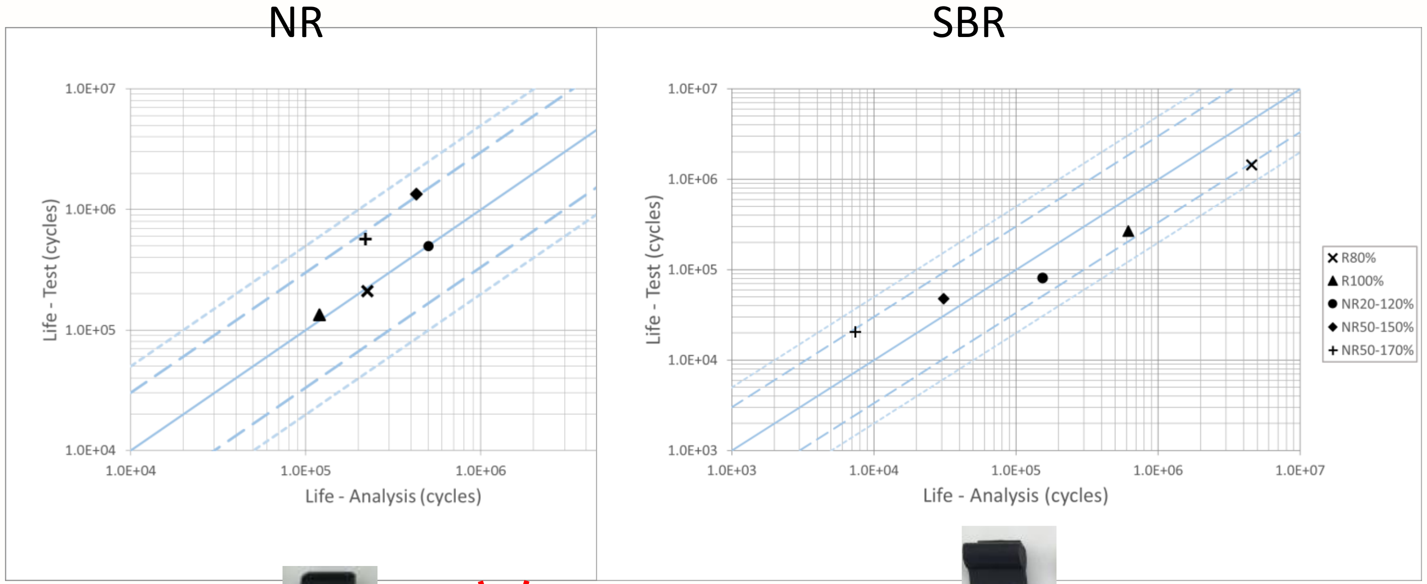
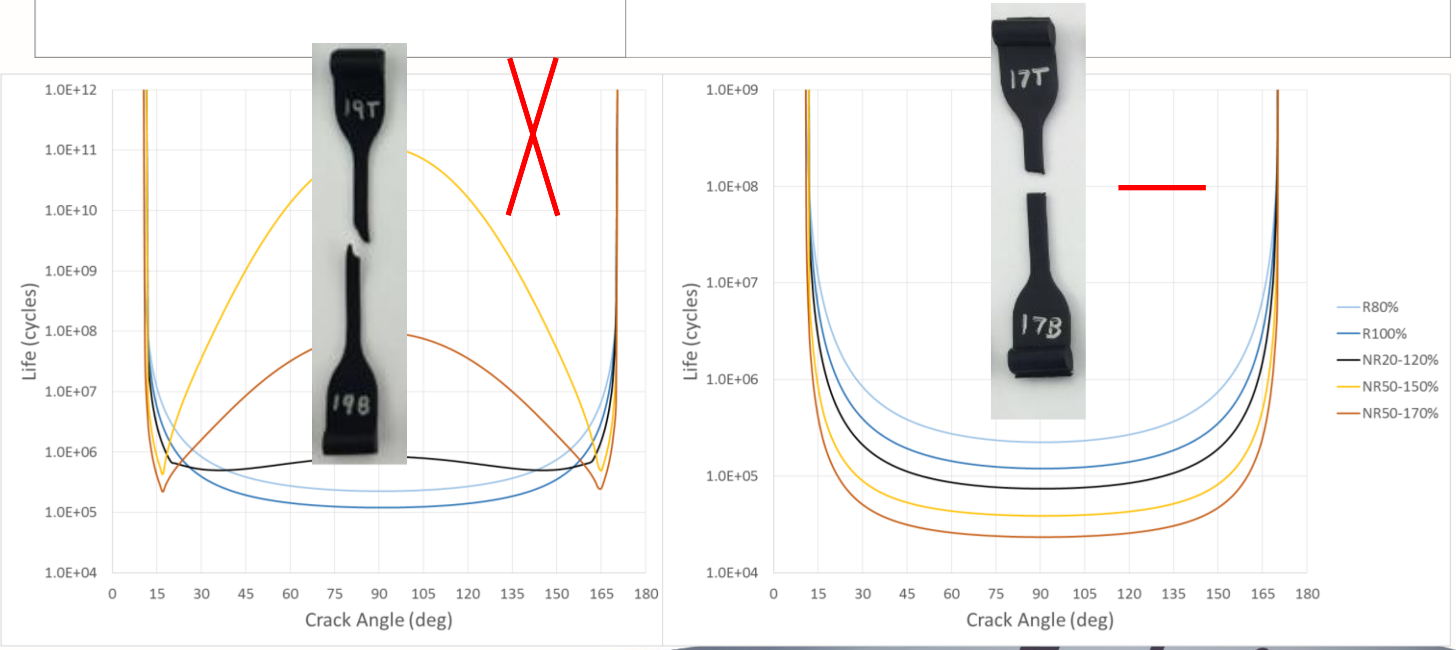
Validation of NR vs. SBR life predictions (nonrelaxing)



- Life predicted to within 3x
- Crack orientation predicted to within ±5°



Endurica CL™
Fatigue Analysis Software

CATERPILLAR®

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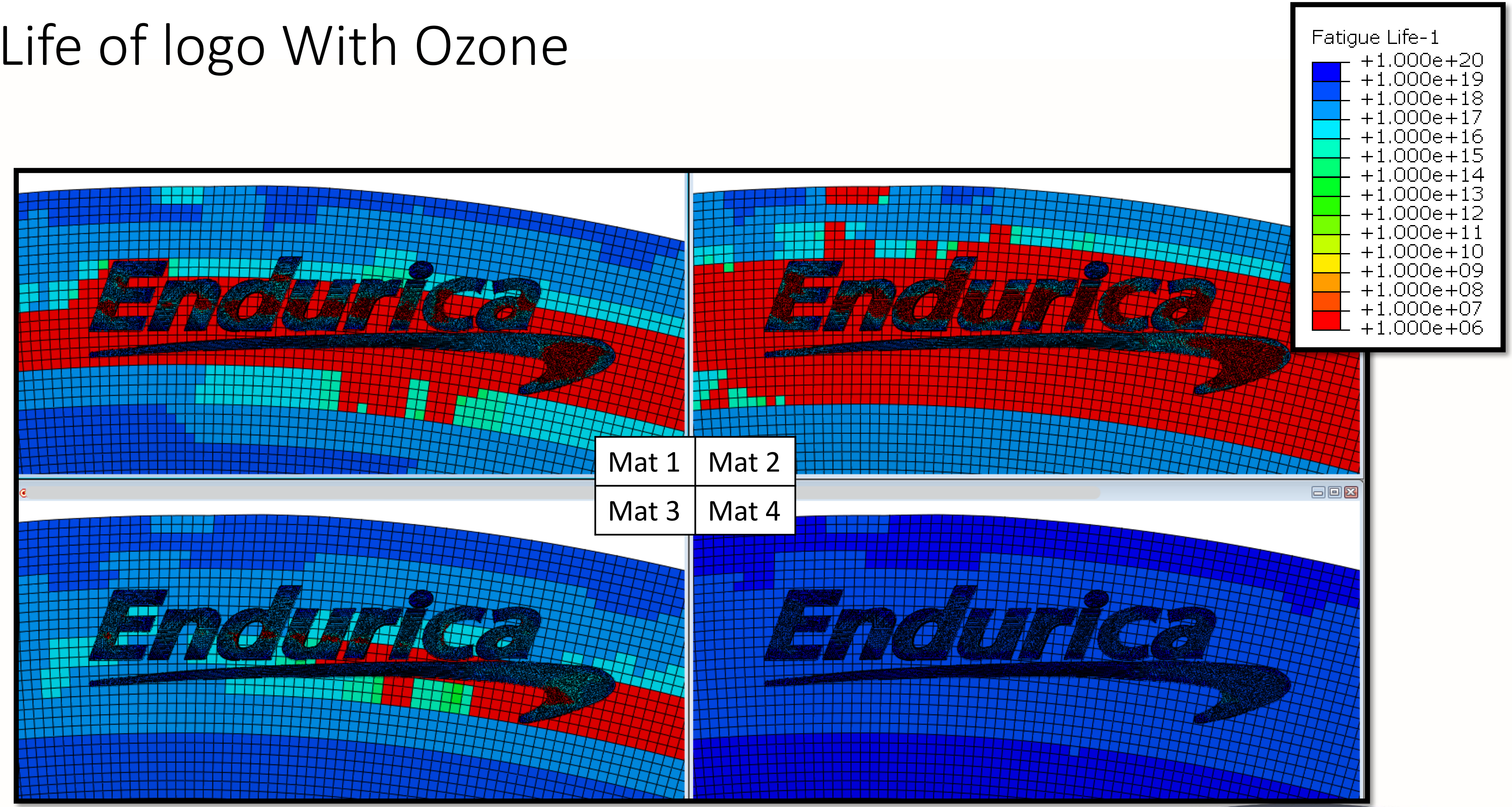
Get Durability Right

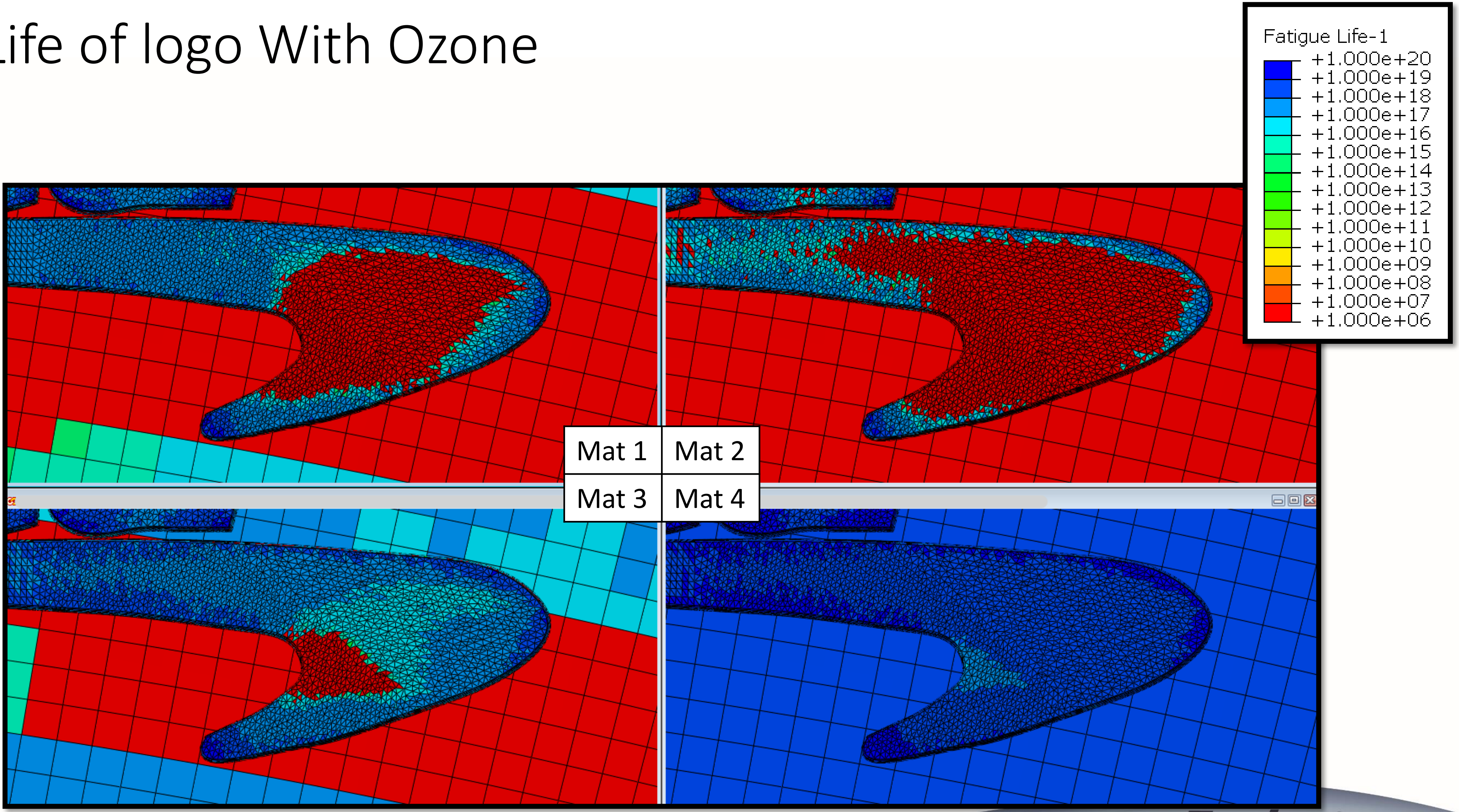
Ozone Attack: NR/EPDM Blends

FORMULARY		ACE Target Requirement	Variant 1	Variant 2	Variant 3	Variant 4
First Pass						
NR	CV60		100.00	80.00	70.00	50.00
EPDM	Royalene 301T		-	20.00	30.00	50.00
	N330		45.00	45.00	45.00	45.00
	790 Oil		8.00	8.00	8.00	8.00
	Zinc Oxide		5.00	5.00	5.00	5.00
	Stearic Acid		2.00	2.00	2.00	2.00
	Sulfur		0.80	0.80	0.80	0.80
	Vultac 710		1.00	1.00	1.00	1.00
	TBBS		1.00	1.00	1.00	1.00
	ZBDC		1.00	1.00	1.00	1.00

Life of logo With Ozone



Life of logo With Ozone



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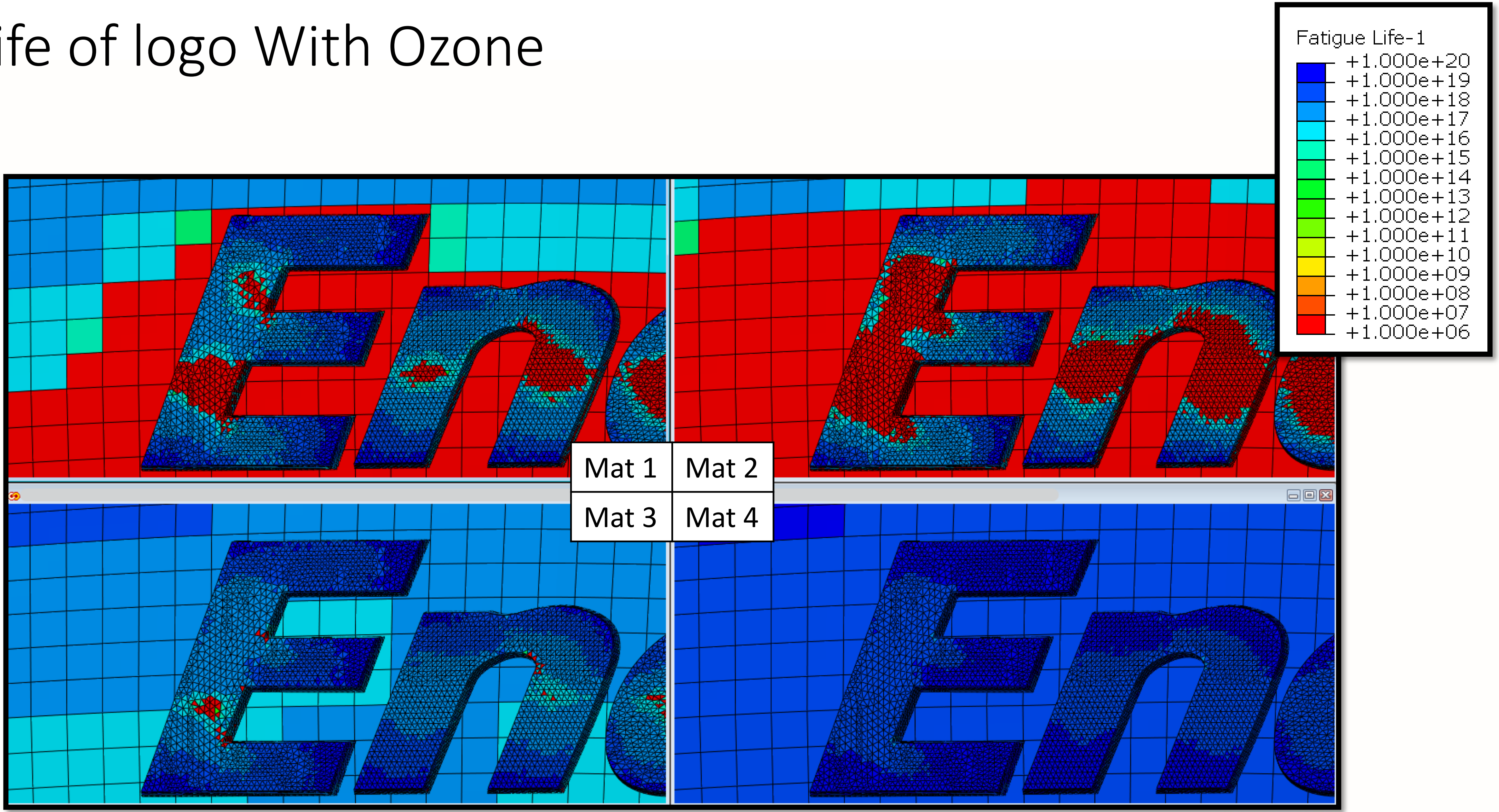
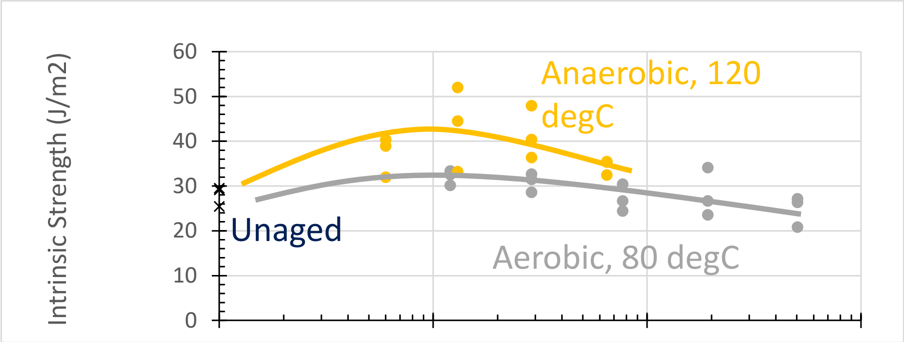
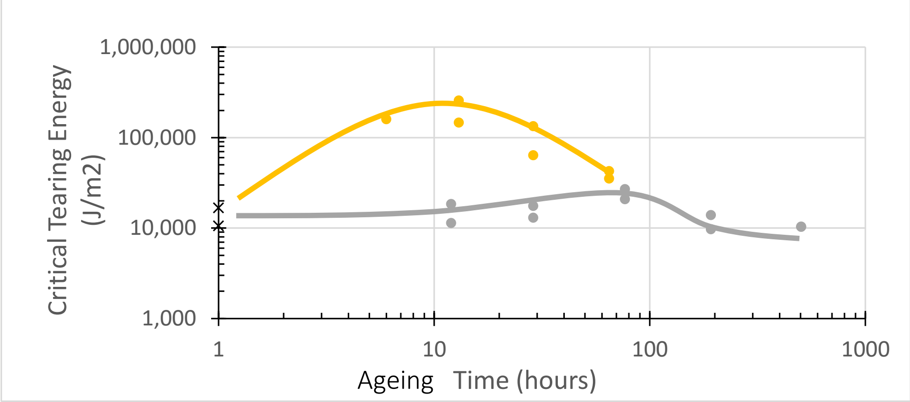
Life of logo With Ozone

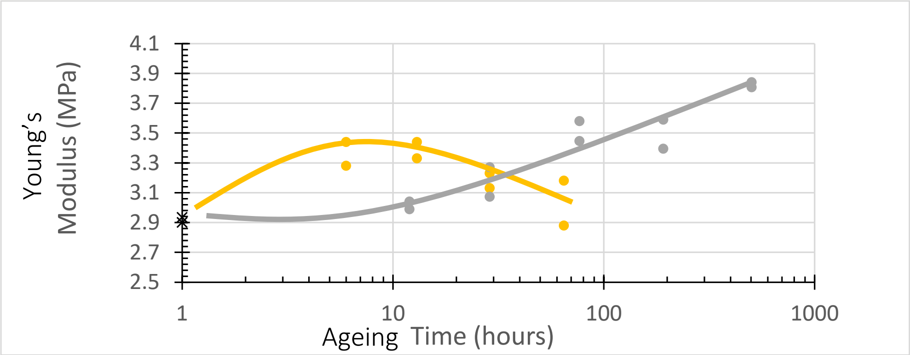


Results: T_0, T_c, E evolution

Experimental results from paper #A29. Thanks to Ed Terrill (ARDL) and Radek Stocek (Coesfeld) for experimental results.








```
!Aerobic
AGEING_TYPE=ARRHENIUS
E_ACTIVATION=50000 ! J/mol
MASTERTEMP=80 ! degC
GASCONSTANT=8.314 ! J/mol/degC
ABSZERO=-273 ! degC
MASTERCURVE=TIME, THRESHOLD, TCR
0,    0.028,  13.650, 2.92
12,   0.032,  14.950, 3.01
28.8, 0.031,  15.300, 3.17
76.8, 0.027,  23.950, 3.51
192,  0.028,  11.810, 3.49
504,  0.025,  10.350, 3.82
1000, 0.020,   5.000, 4.0 ! extr
```

```
!Anaerobic
AGEING_TYPE=ARRHENIUS
E_ACTIVATION=50000 ! J/mol
MASTERTEMP=120 ! degC
GASCONSTANT=8.314 ! J/mol/degC
ABSZERO=-273 ! degC
MASTERCURVE=TIME, THRESHOLD, TCRITICAL, MODULUS
0,    0.028,  13.650, 2.92
6,    0.037, 113.050, 3.36
13,   0.040, 202.500, 3.385
28.8, 0.042,  99.050, 3.18
64.8, 0.034,  39.000, 3.03
144,  0.026,  16.000, 2.9 ! extrap
1000, 0.020,   5.000, 2.8 ! extrap
```

Endurica DT™
Incremental Fatigue Solver

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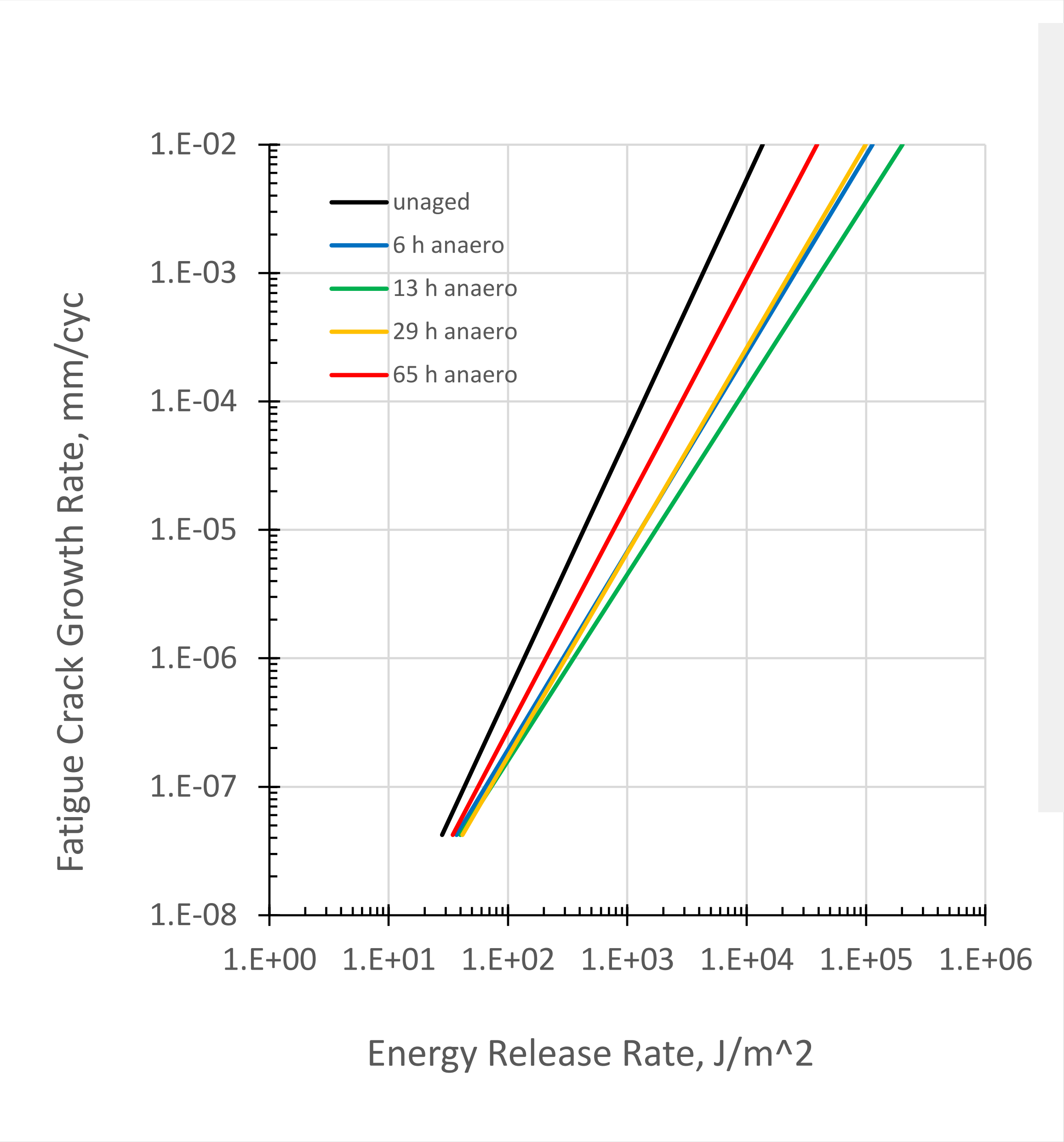
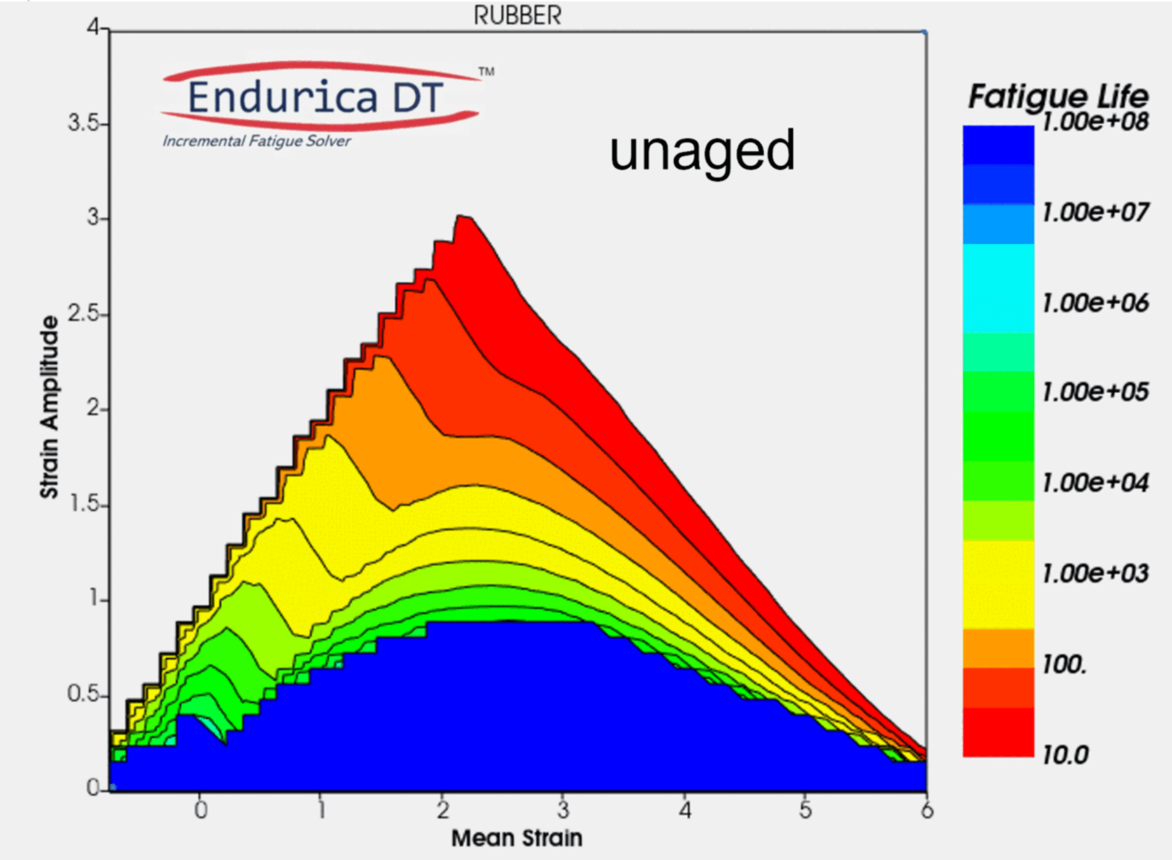
Ageing Effects





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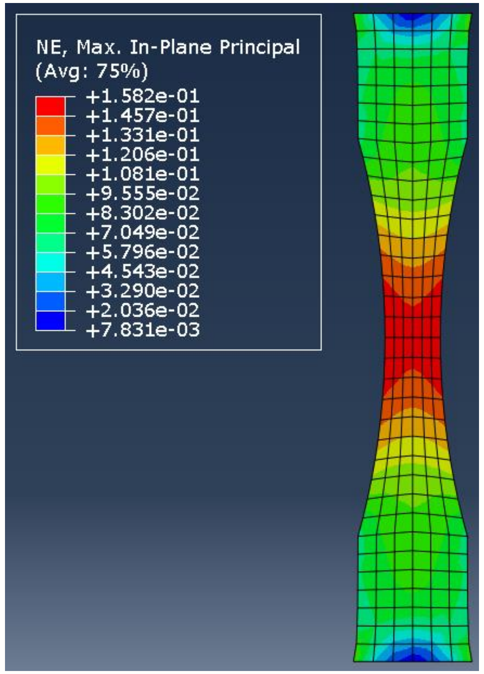
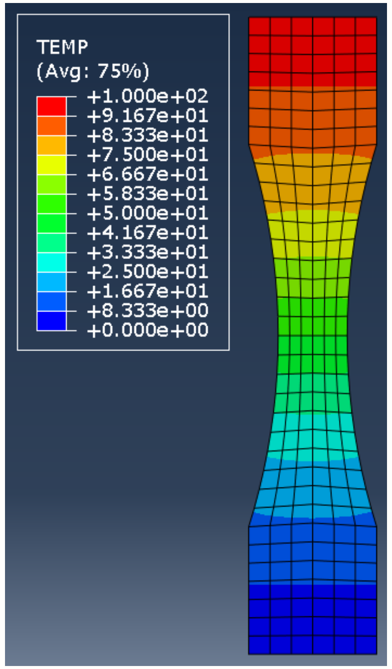
Demo – Fatigue under Temperature Gradient

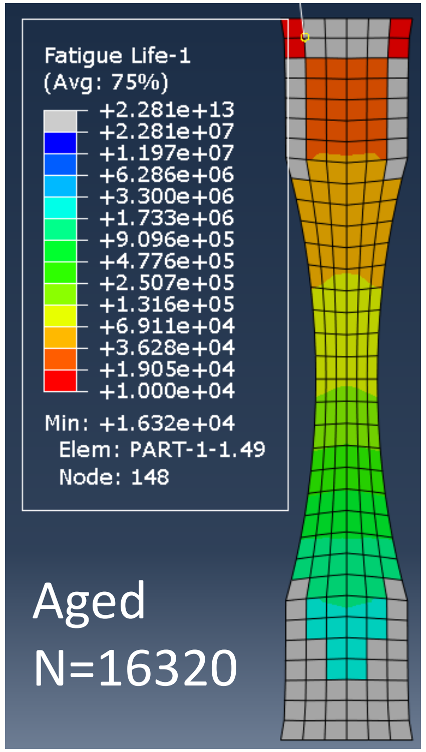


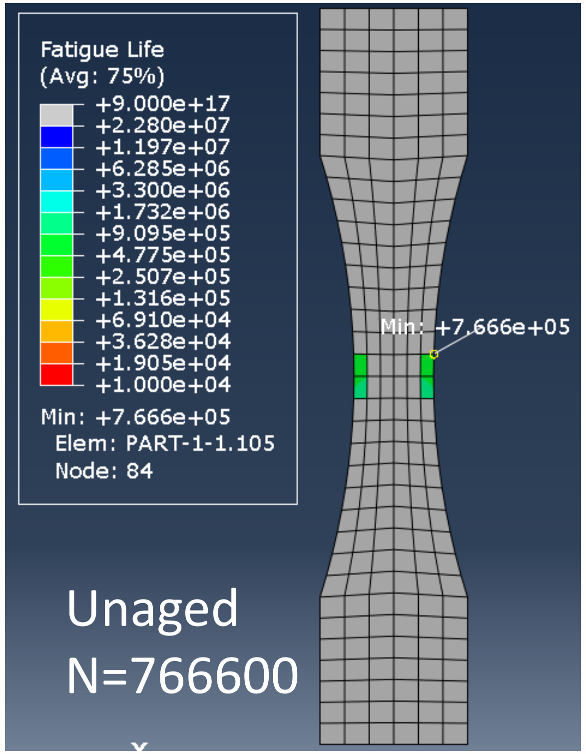


N=10000 cycles
HISTPERIOD=6.94E-4 ! days (=1 min)

```
MAT=FILLEDNR
ELASTICITY_TYPE=NEOHOOKEAN
SHEAR_MODULUS=3 ! MPa
BULK_MODULUS=3000 ! MPa
FATIGUE_TYPE=LAKELINDLEY
FLAWSIZE=0.1   ! mm
FLAWCRIT=1.0   ! mm
RC=1E-3    ! (mm/cycle)
TCRITICAL=10.0 ! kJ/m^2
THRESHOLD=0.04 ! kJ/m^2
TRANSITION=0.45 ! kJ/m^2
F0=2
TEMPCOEF=0.03 ! 1/DEGC
TEMPREF=20     ! DEGC
AGEING_TYPE=ARRHENIUS
E_ACTIVATION=49e6 ! mJ/mol
MASTERTEMP=23 ! degC
GASCONSTANT=8314.0 ! mJ/mol/degC
ABSZERO=-273 ! degC
MASTERCURVE=TIME, THRESHOLD, TCRITICAL, MODULUS
0.0    0.040 10.000 1.0
1.0    0.039  9.500 0.97
3.0    0.038  9.000 0.98
10.0   0.037  8.500 0.95
30.0   0.030  8.000 1.0
100.0  0.028  7.750 1.1
300.0  0.020  6.000 1.2
1000.0 0.010  3.000 1.3
```

Aged vs. Unaged Fatigue Life





Validation of Block Cycle schedule life prediction

2022-01-0760 Published 29 Mar 2022

SAE INTERNATIONAL

Fatigue Life Prediction and Correlation of Engine Mount Elastomeric Bushing using A Crack Growth Approach

C Elango, Sathish Kumar Pandi, and Roshan N Mahadule FCA Engineering India Pvt, Ltd.

Touhid Zarrin-Ghalami FCA US LLC

Citation: Elango, C., Pandi, S.K., Mahadule, R.N., and Zarrin-Ghalami, T., "Fatigue Life Prediction and Correlation of Engine Mount Elastomeric Bushing using A Crack Growth Approach," SAE Technical Paper 2022-01-0760, 2022, doi:10.4271/2022-01-0760.

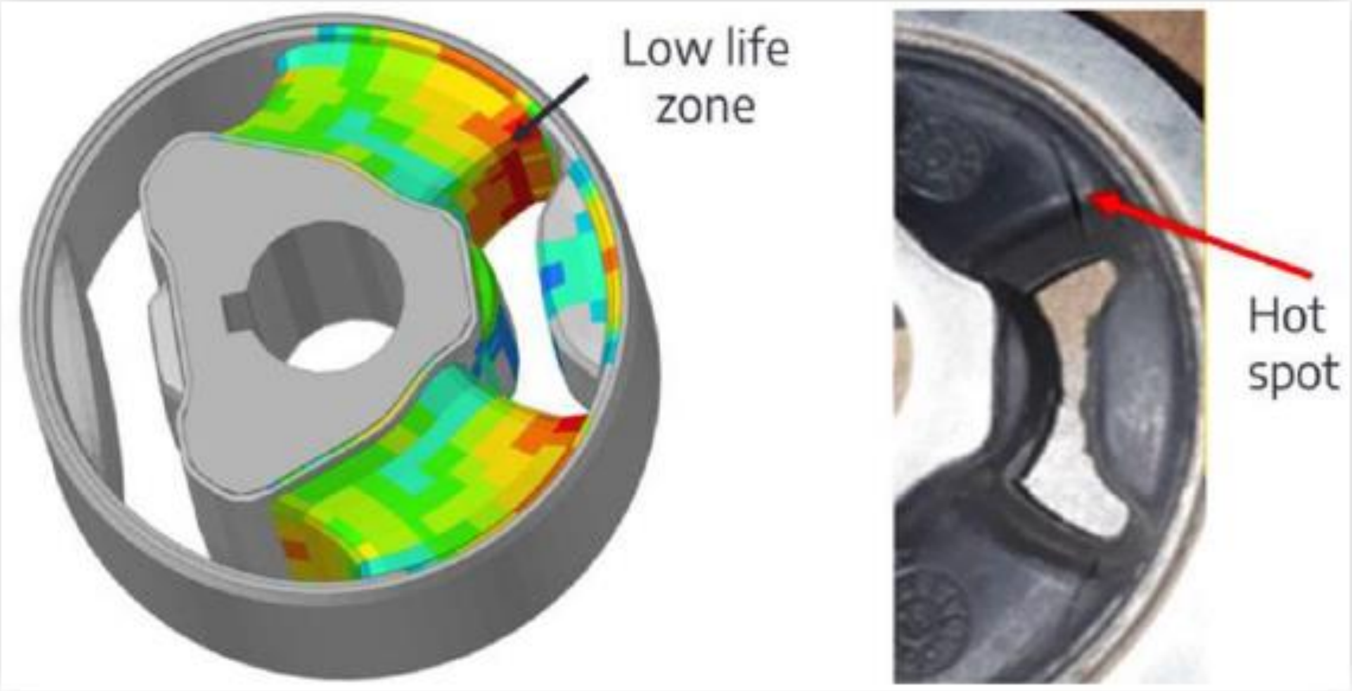


TABLE 1 Test and CAE comparison for Fatigue Life.

Fatigue Life (blocks)				
In CAE (Virtual simulation)	**In Physical test**			
520	540	510	540	500
	Average = 523			

- Failure mode predicted
- Life predicted to within repeatability of test

Endurica CL™ Fatigue Analysis Software

Endurica EIE™ Fast Loads Processing

Endurica Get Durability Right

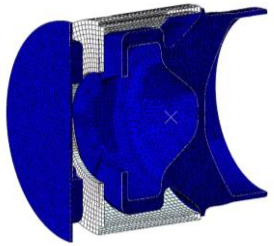
Full Vehicle History

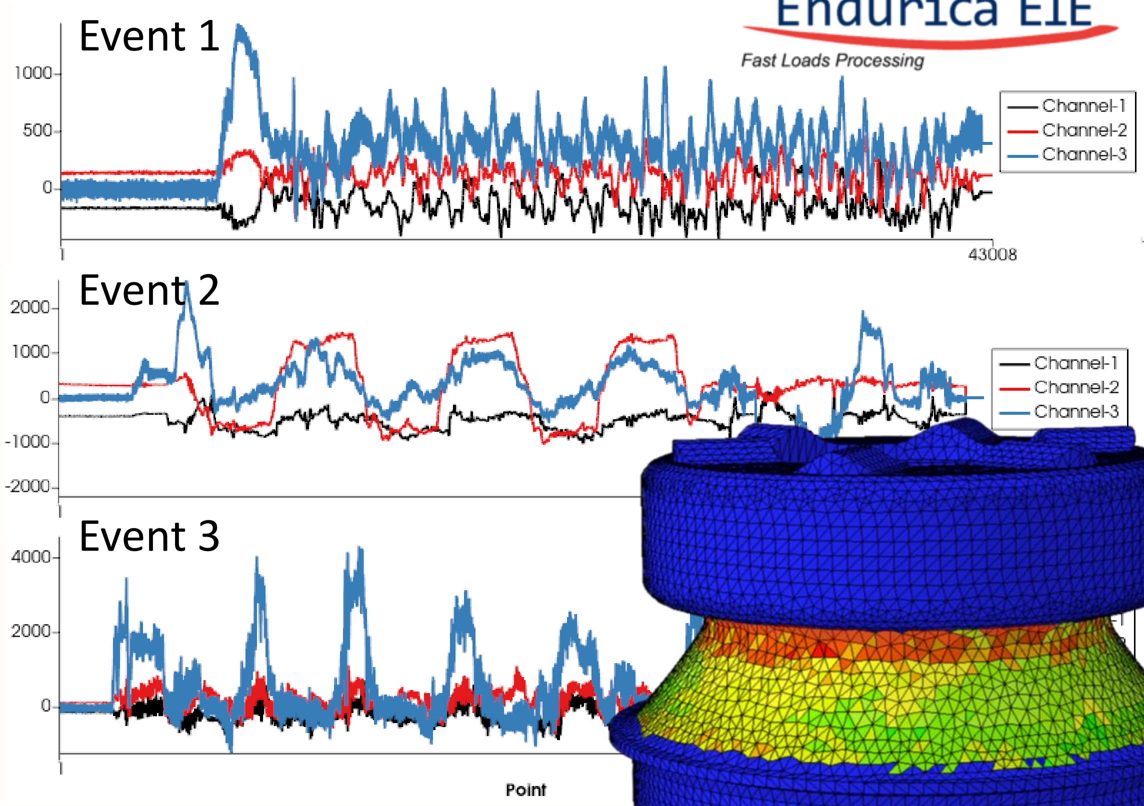
Endurica CL™
Fatigue Analysis Software

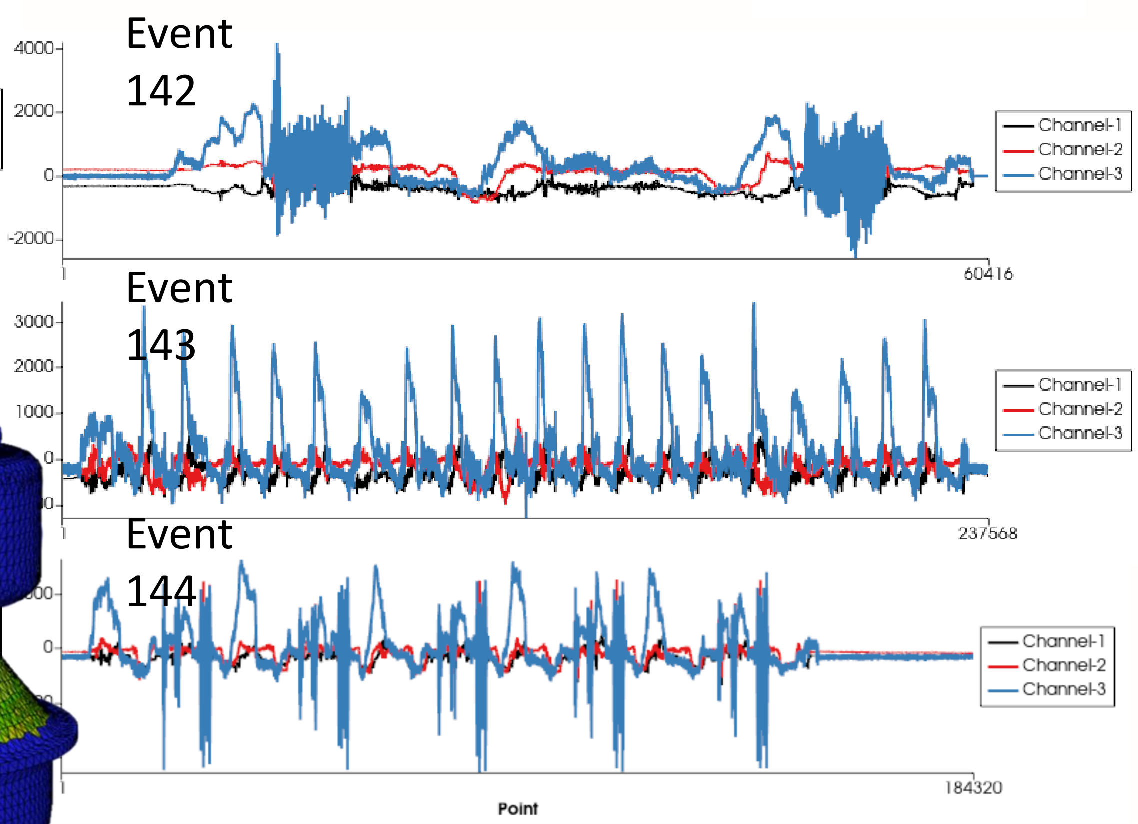
Endurica DT™
Incremental Fatigue Solver

Endurica EIE™
Fast Loads Processing

Final Life: 9.42 Repeats
Run Times
- Abaqus Map: 57 hour on 11 CPUs
- EIE Interpolation: 8 hour on 32 Threads
- Fatigue Solve 25 hour on 7 CPUs
- Total: 90 hours







Endurica
Get Durability Right

Summary

- Material Models
- Procedures
- Validation
- Capacity

- Get Durability Right!

OEMs expect virtual proof of durability from component suppliers on bids for new business.

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Get Durability Right®

Q & A

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Get Durability Right®

Solutions for Elastomer Durability