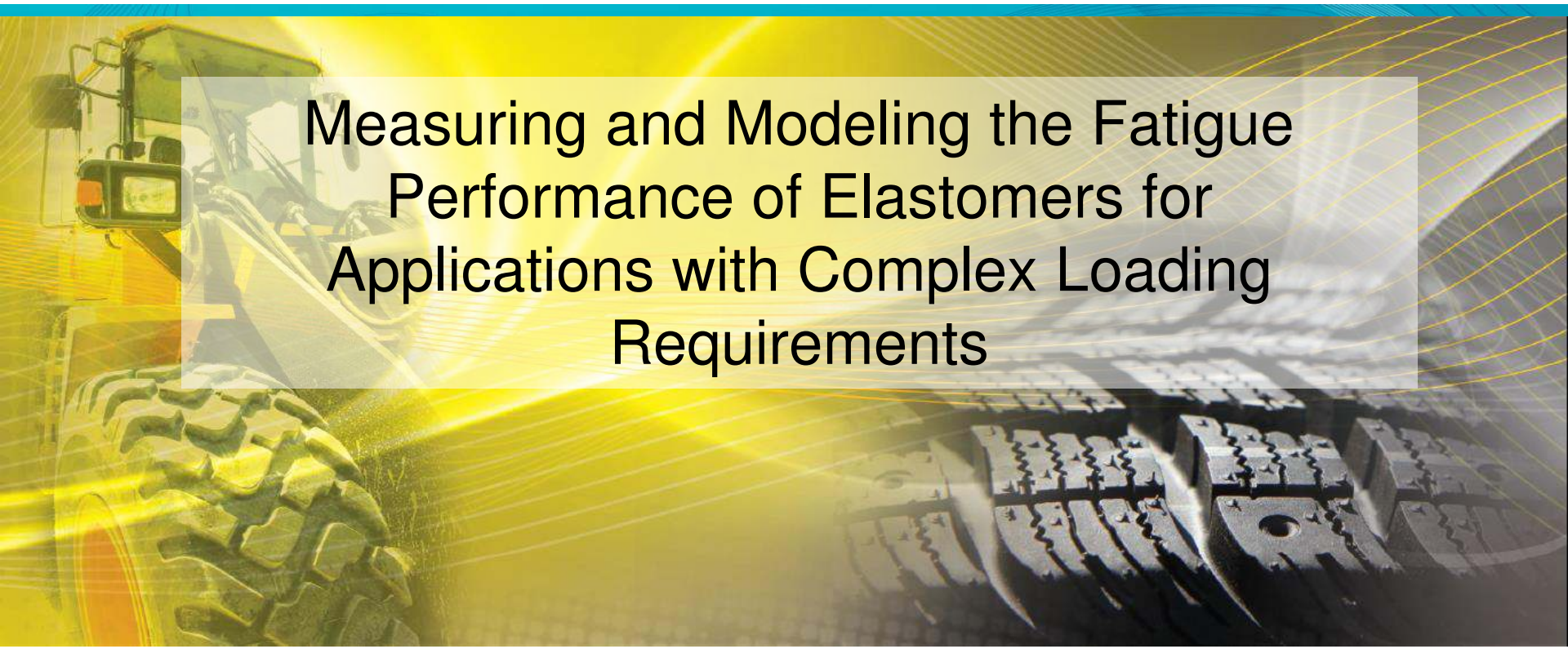

Measuring and Modeling the Fatigue Performance of Elastomers for Applications with Complex Loading Requirements

W. V. Mars
Endurica LLC

Energy Rubber Group
16 January 2014

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Accelerating Reliable Design

www.endurica.com

Agenda

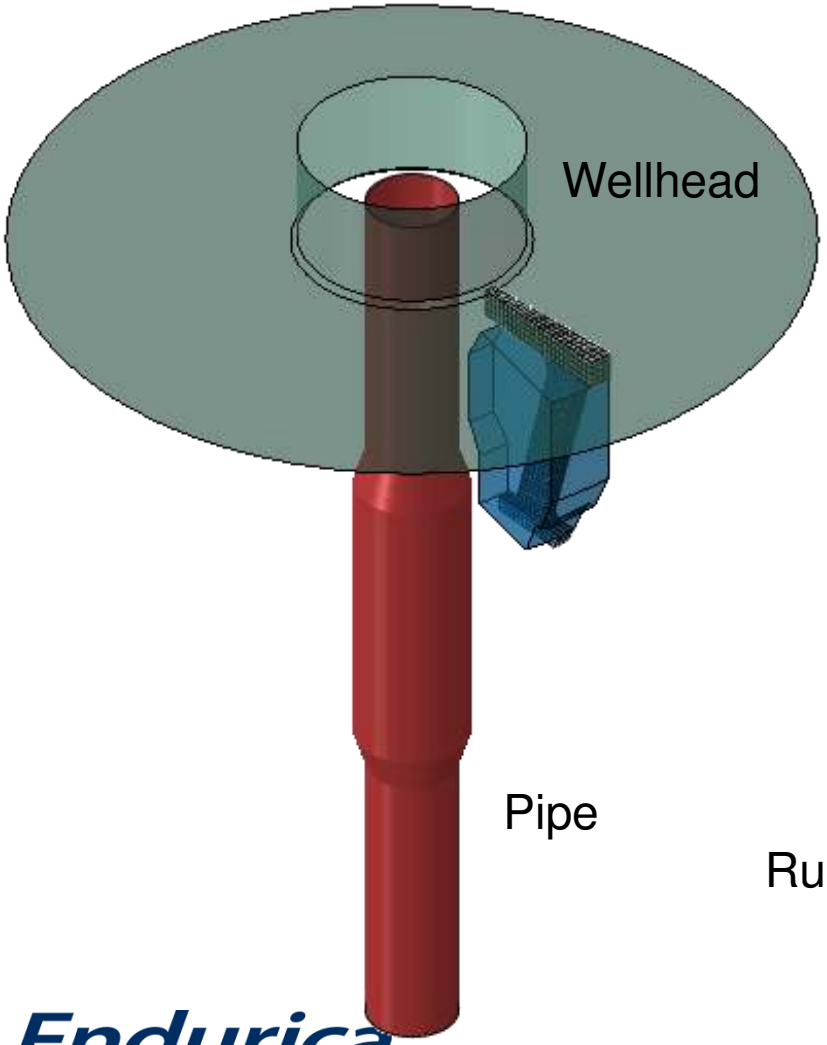
- About Endurica
- Solution Overview
- Case study: Wellhead sealing element
  - Geometry
  - Load History
  - Materials
- Brief fe-safe/rubber tour
- Results

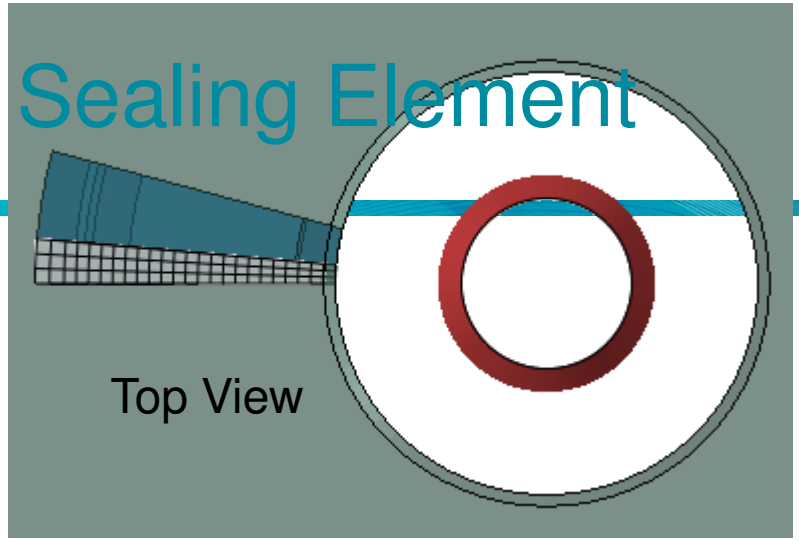
About Endurica LLC

- Mission: Pre-prototype solutions for managing elastomer durability
- Founded in 2008
- 100% focus - elastomers and durability

Case Study: Wellhead Sealing Element

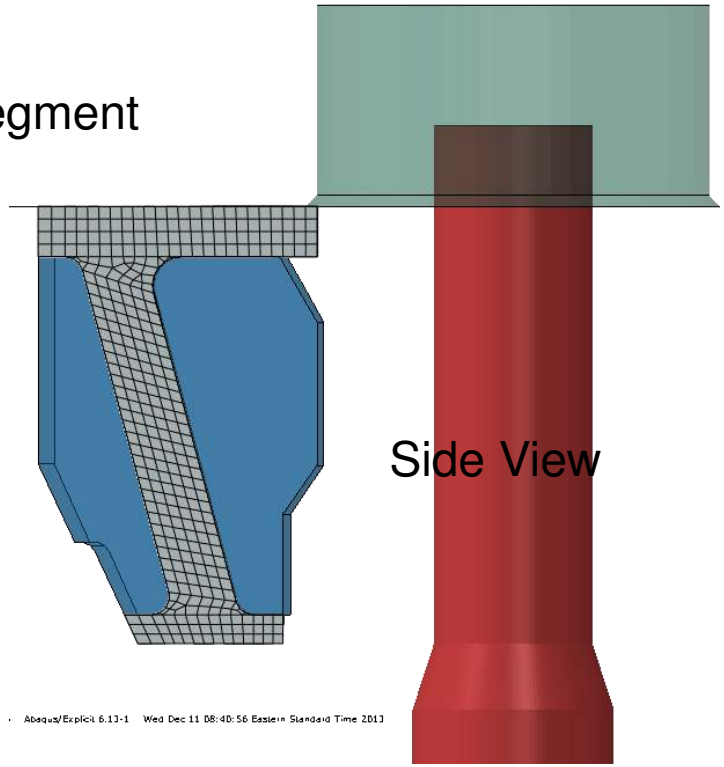
Isometric





Segment

Rubber



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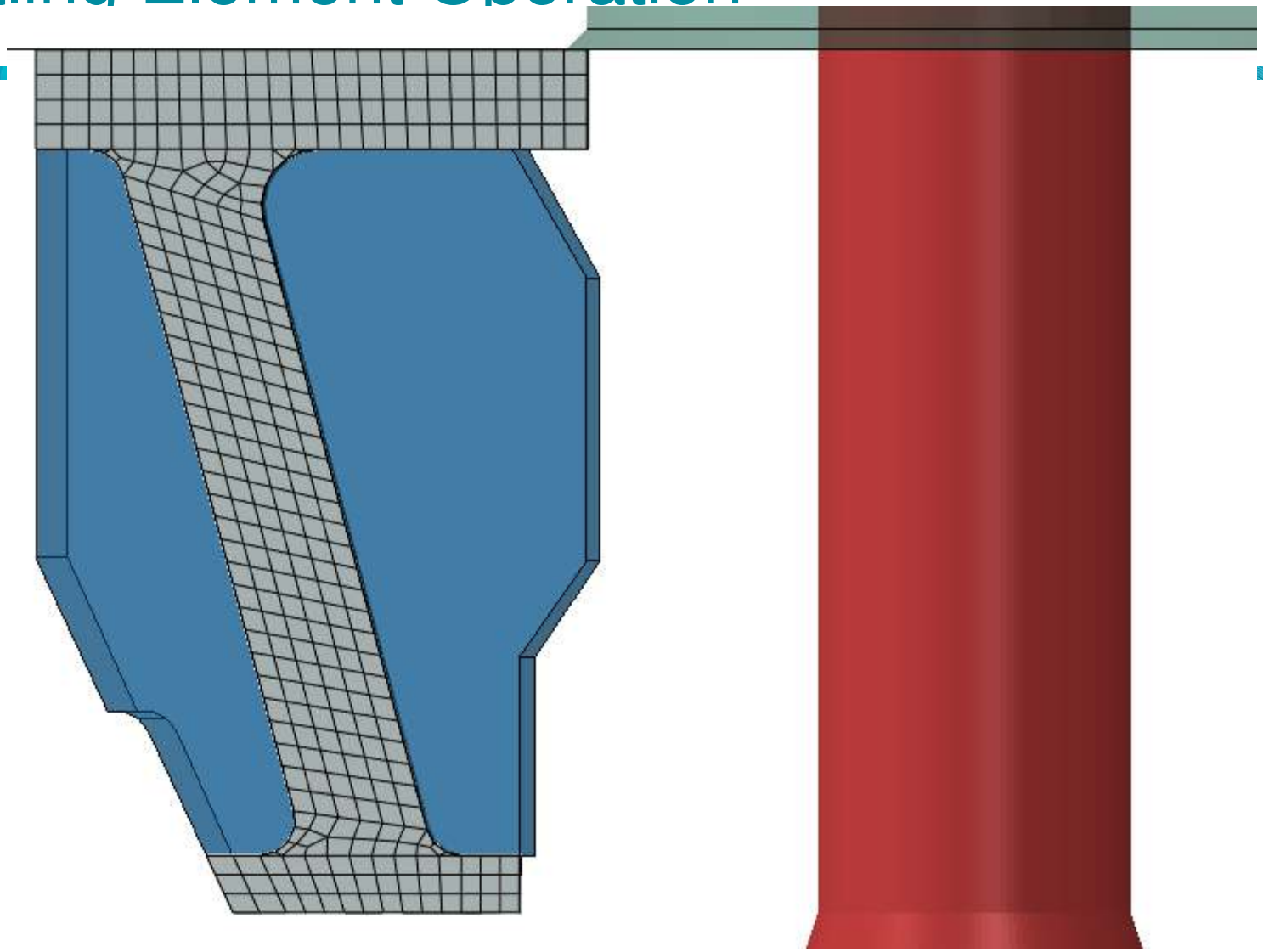
Sealing Element Operation



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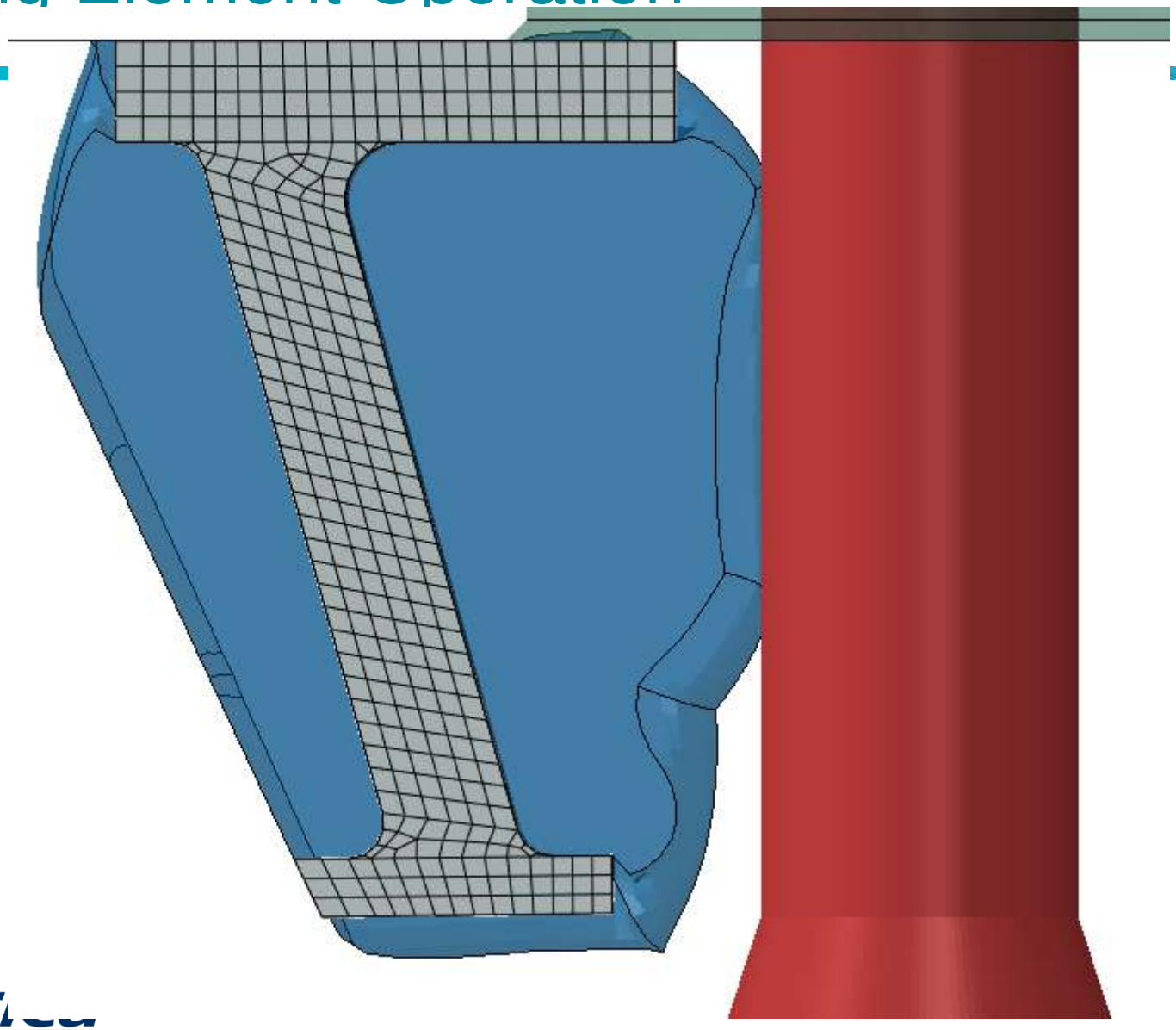
Sealing Element Operation



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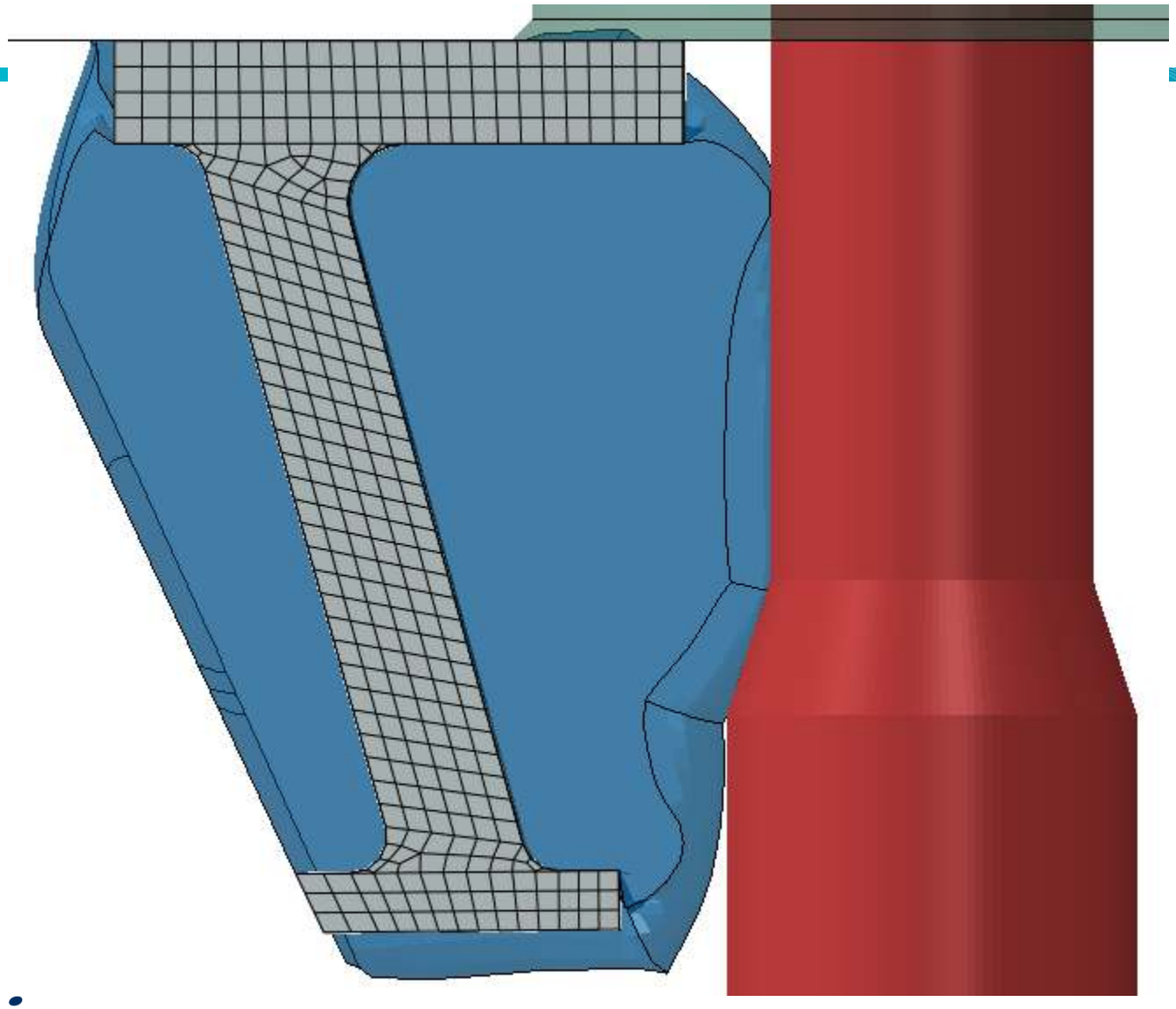

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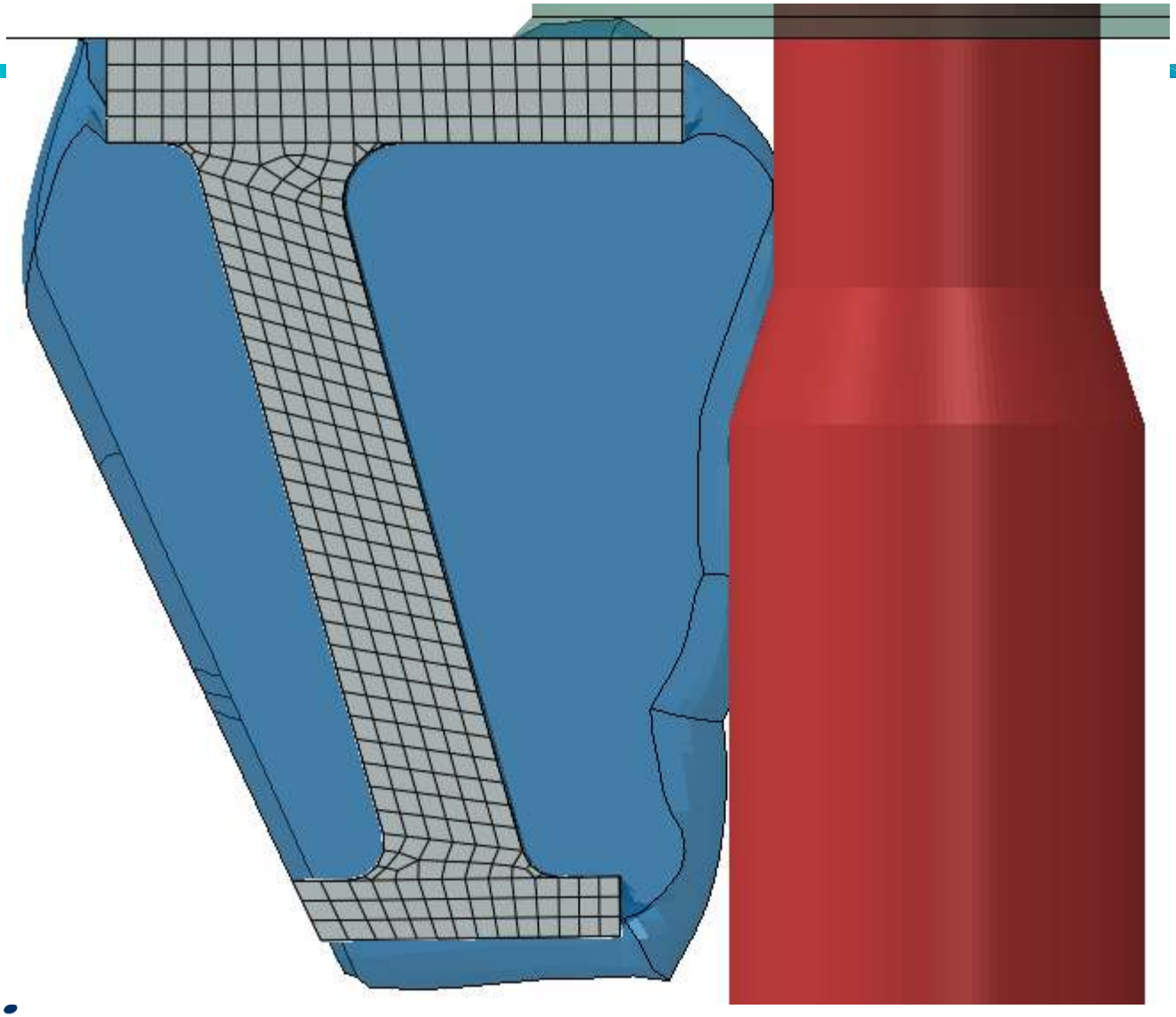

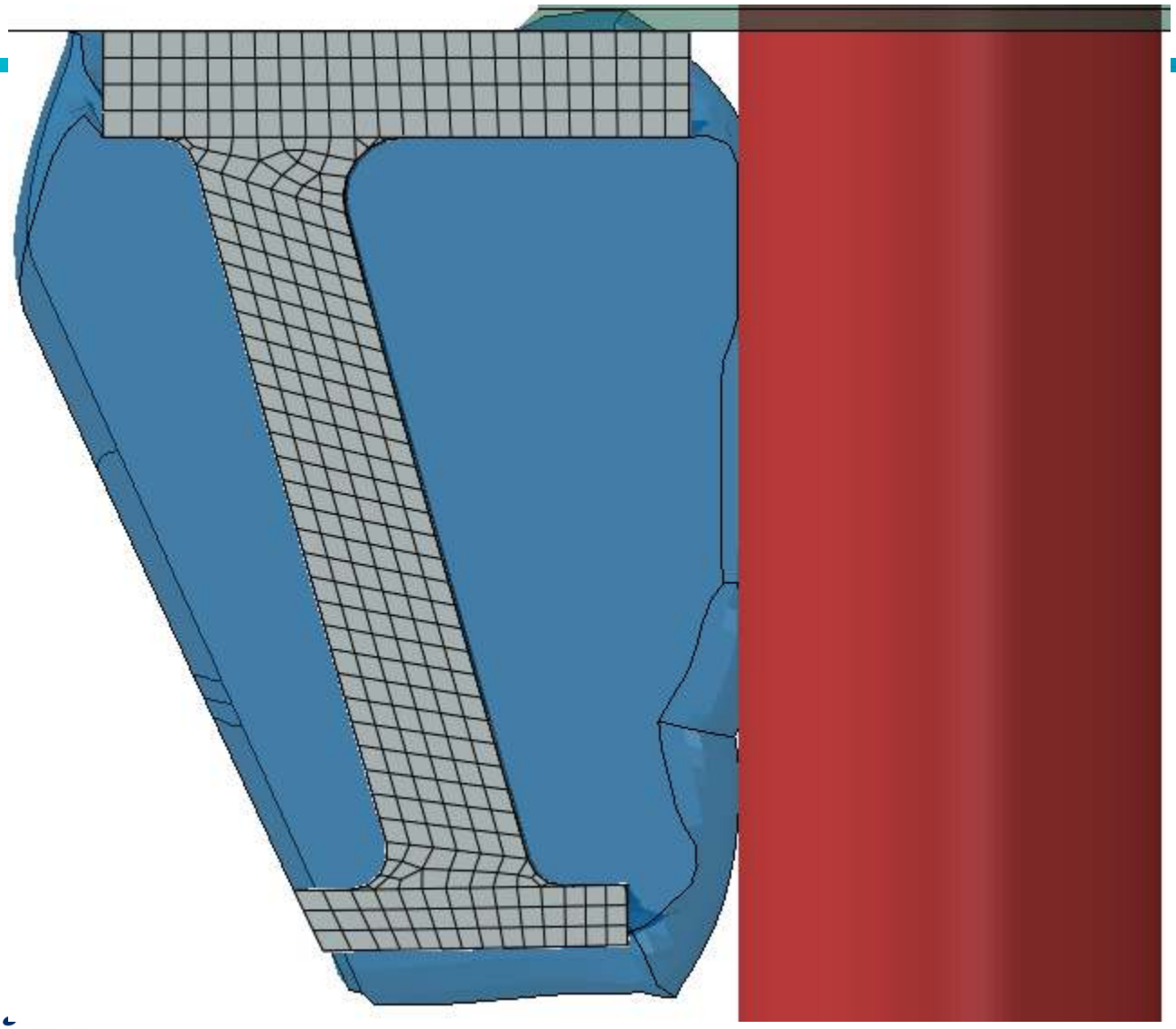

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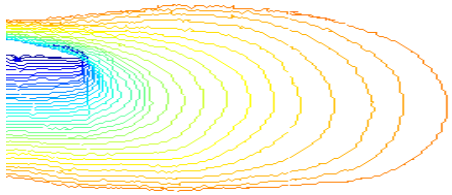
Sealing Element Development Challenges

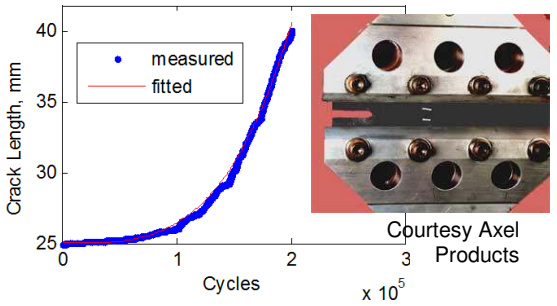
- Technical
  - How many repeats of the operating history can be endured?
  - Where will part fail?
  - What compound will give best life?
  - Diagnostics – what specific features, loads, times are critical?
  - Optimal operating procedures (ie seal ID vs pipe OD) for seal life?
- Management
  - Prototyping / Manufacturing Resources
  - Testing Resources
  - Accurate evaluation vs. limited development time and budget
  - Consequences of failure at prototype or production stages
  - Communication about complex problems

Characterization

Know Your Material



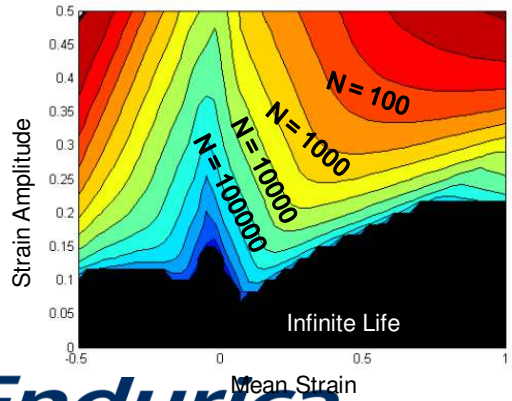
Core Fatigue Test
Fully Relaxing Behavior from both nucleation and fracture mechanical perspectives

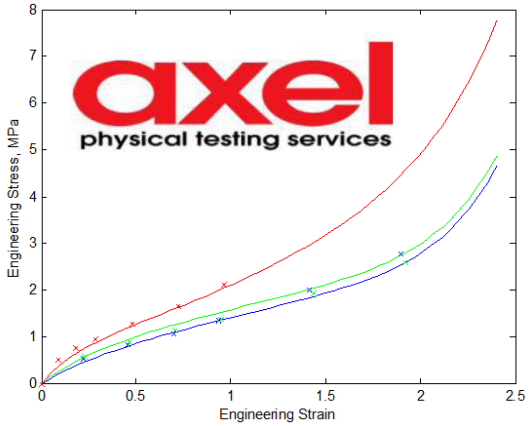


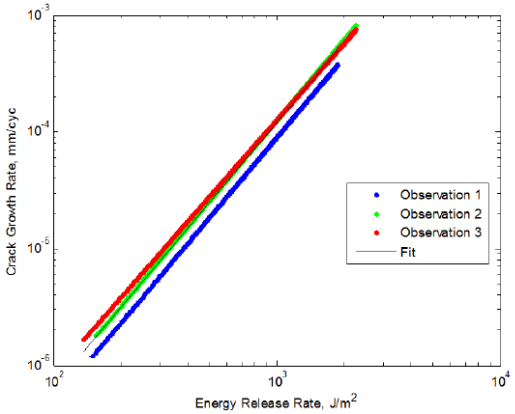
Nonrelaxing Option
Quantify Strain Crystallization, Min and Mean Strain Effects

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

Thermal Option
Quantify dissipative properties, thermal properties, temperature dependence







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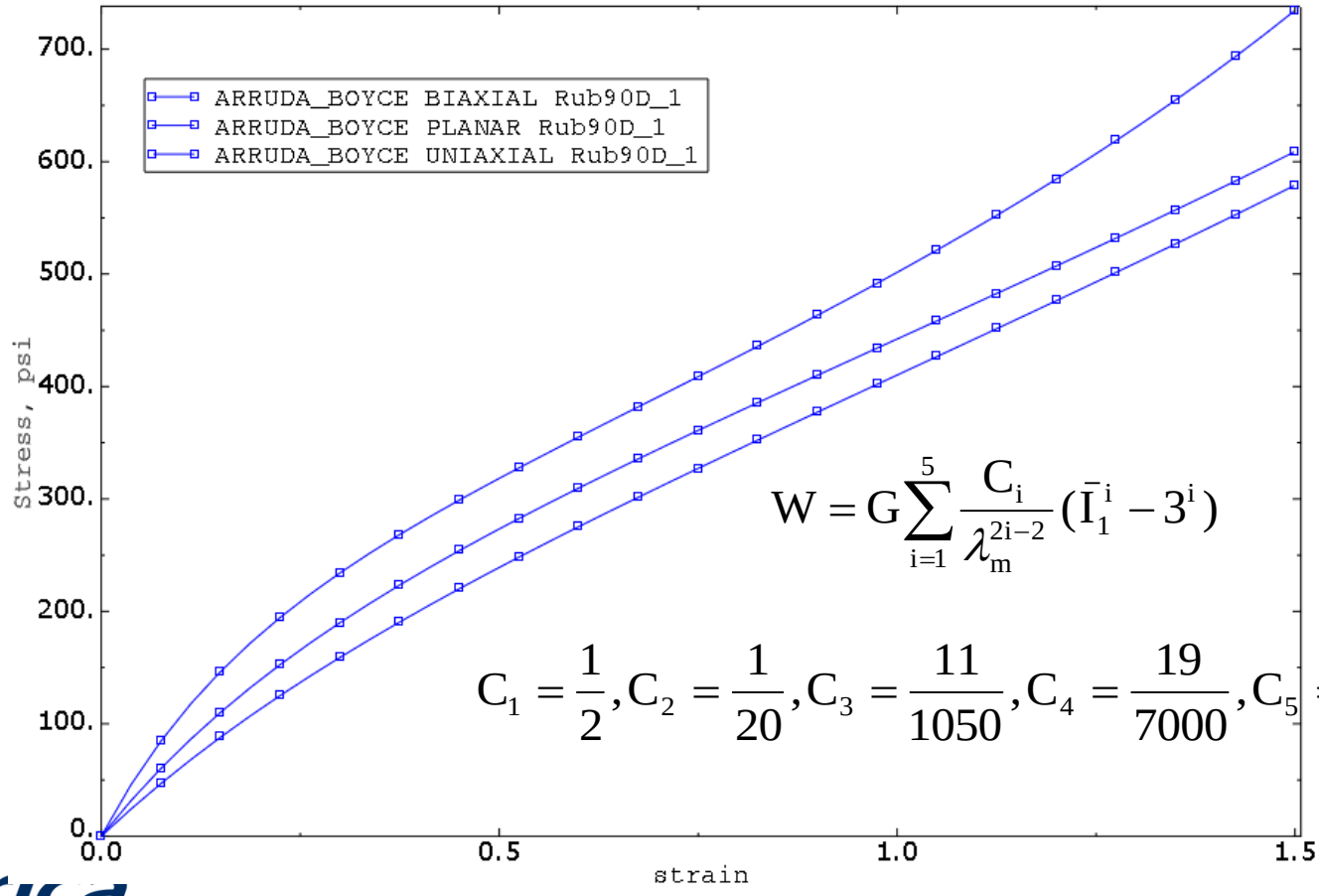
Material Definition – Stress-strain

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



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

$$C_1 = \frac{1}{2}, C_2 = \frac{1}{20}, C_3 = \frac{11}{1050}, C_4 = \frac{19}{7000}, C_5 = \frac{519}{673750},$$

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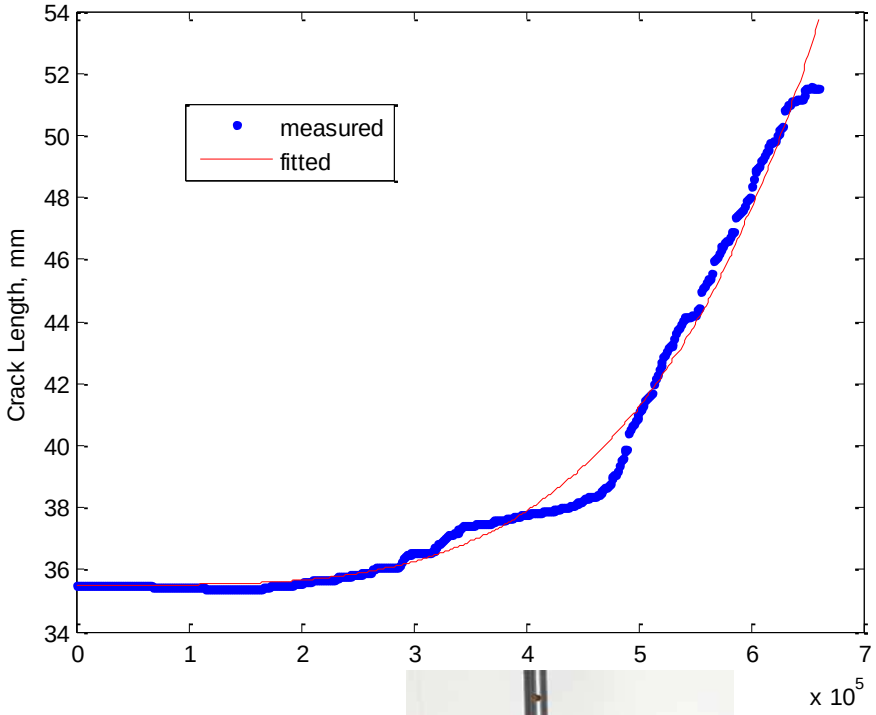
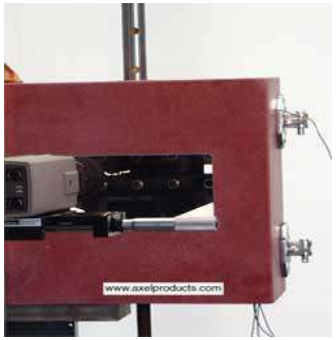
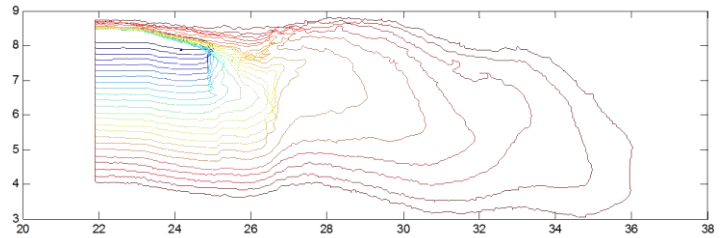
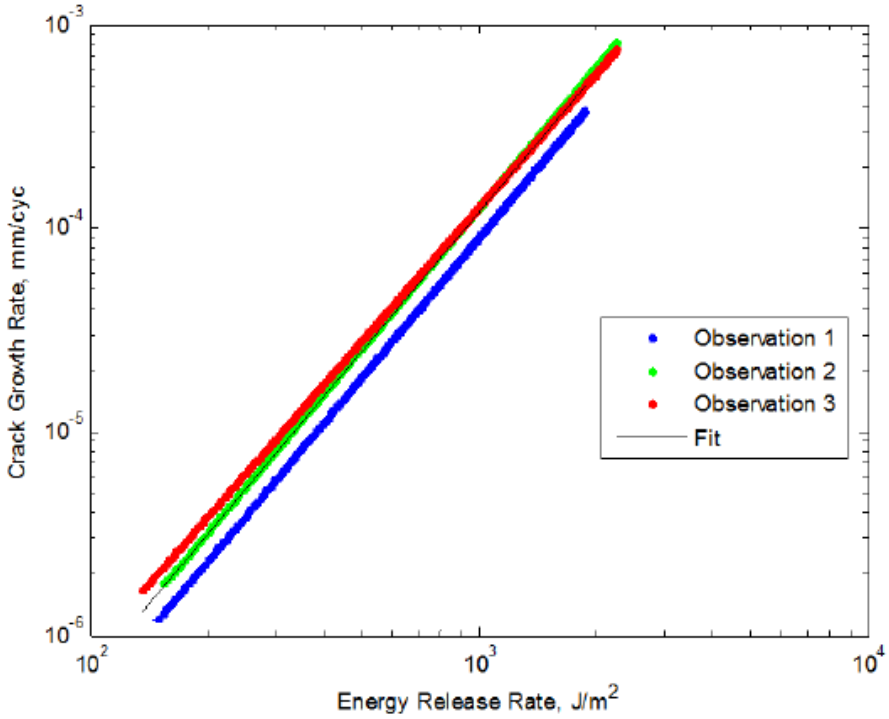
Observed and Fitted Crack Growth









axel physical testing services

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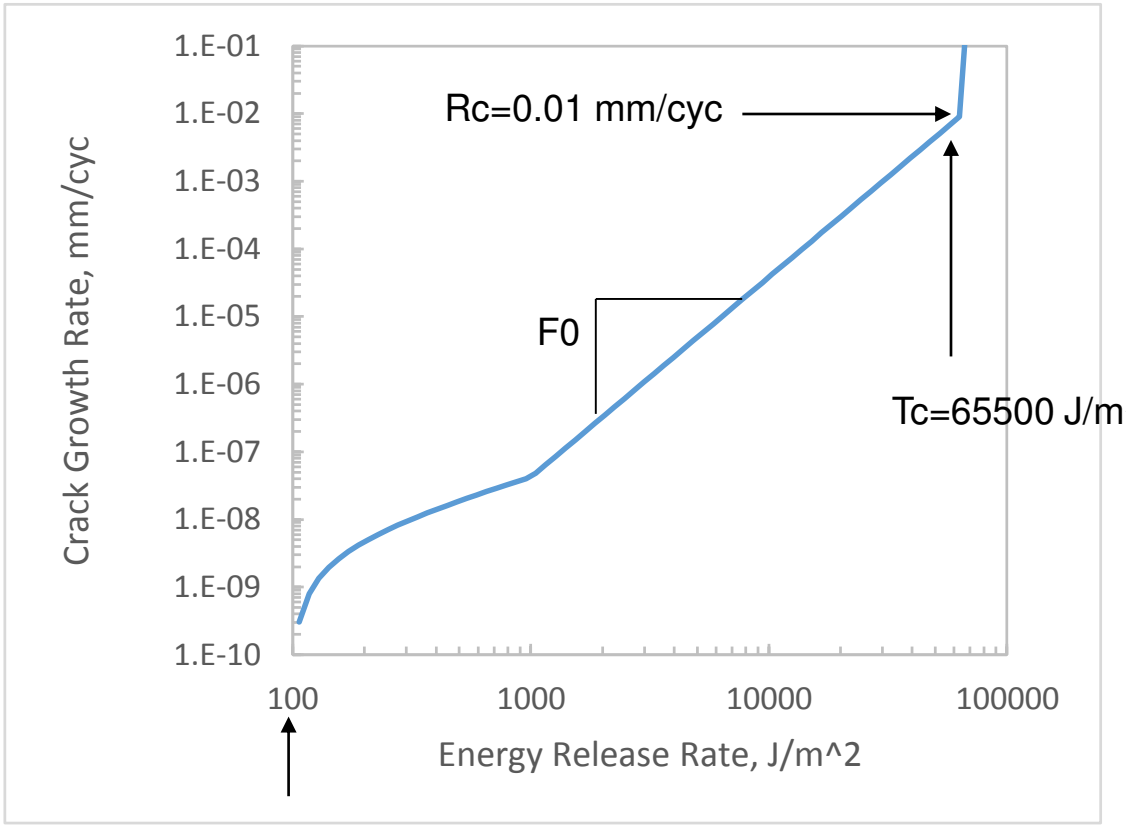
Material Definition: Fatigue Behavior



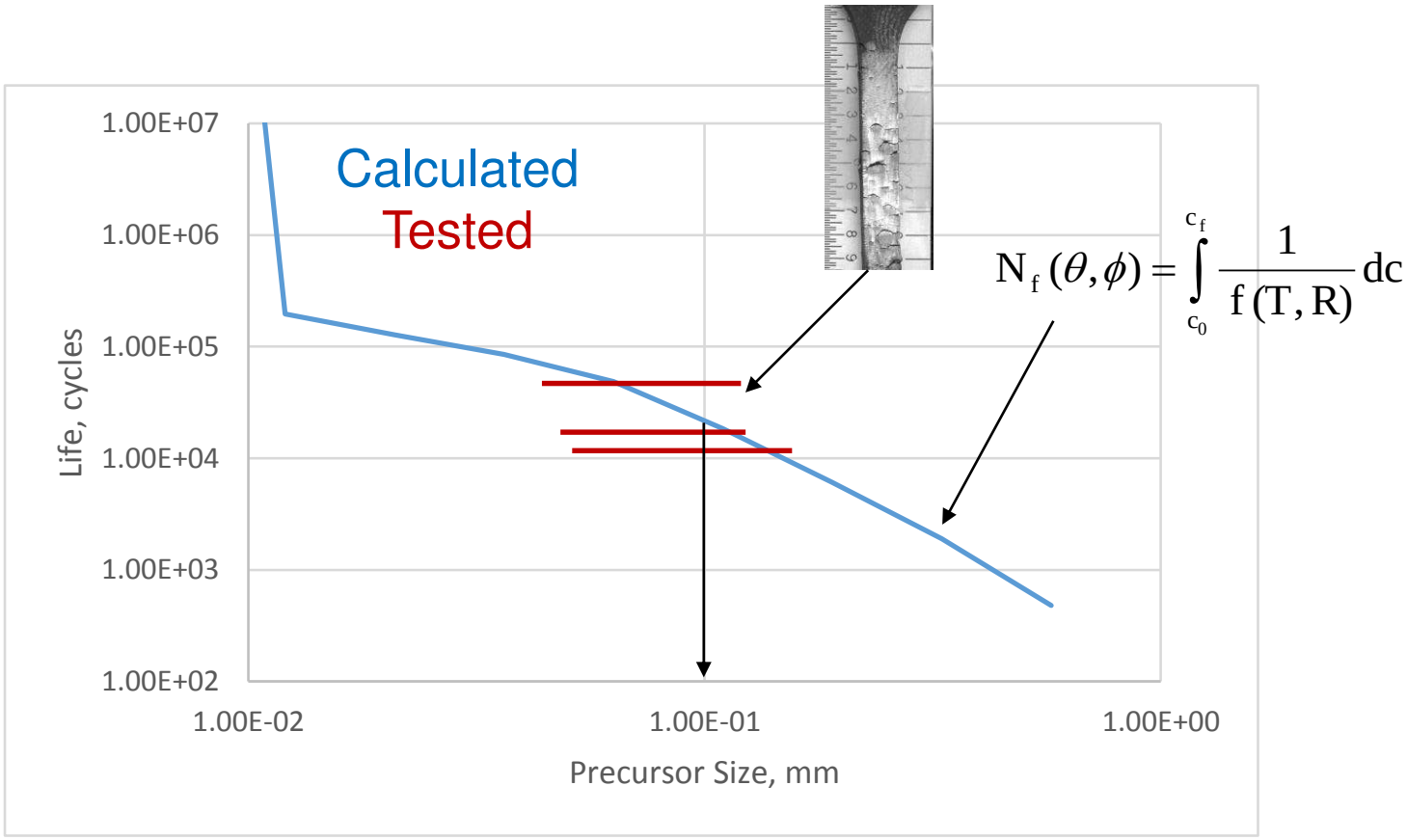
c0=0.100 mm
cf=1.00 mm

$$\frac{dc}{dN} = A(T_{max} - T_o)$$

$$A = \frac{r_c T_t^F}{T_c^F (T_t - T_o)}$$

$$\frac{dc}{dN} = r_c \left(\frac{T_{max}}{T_c} \right)^F$$

Material Definition Crack Precursor Size



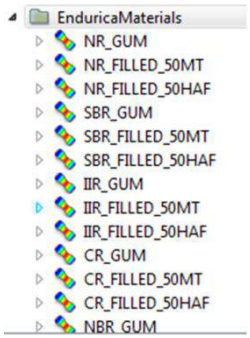
Solution Overview

fe-safe/Rubber™ powered by Endurica

Elastomer Durability Software for Finite Element Models

Analysis Software

Pre-defined Materials



Documentation

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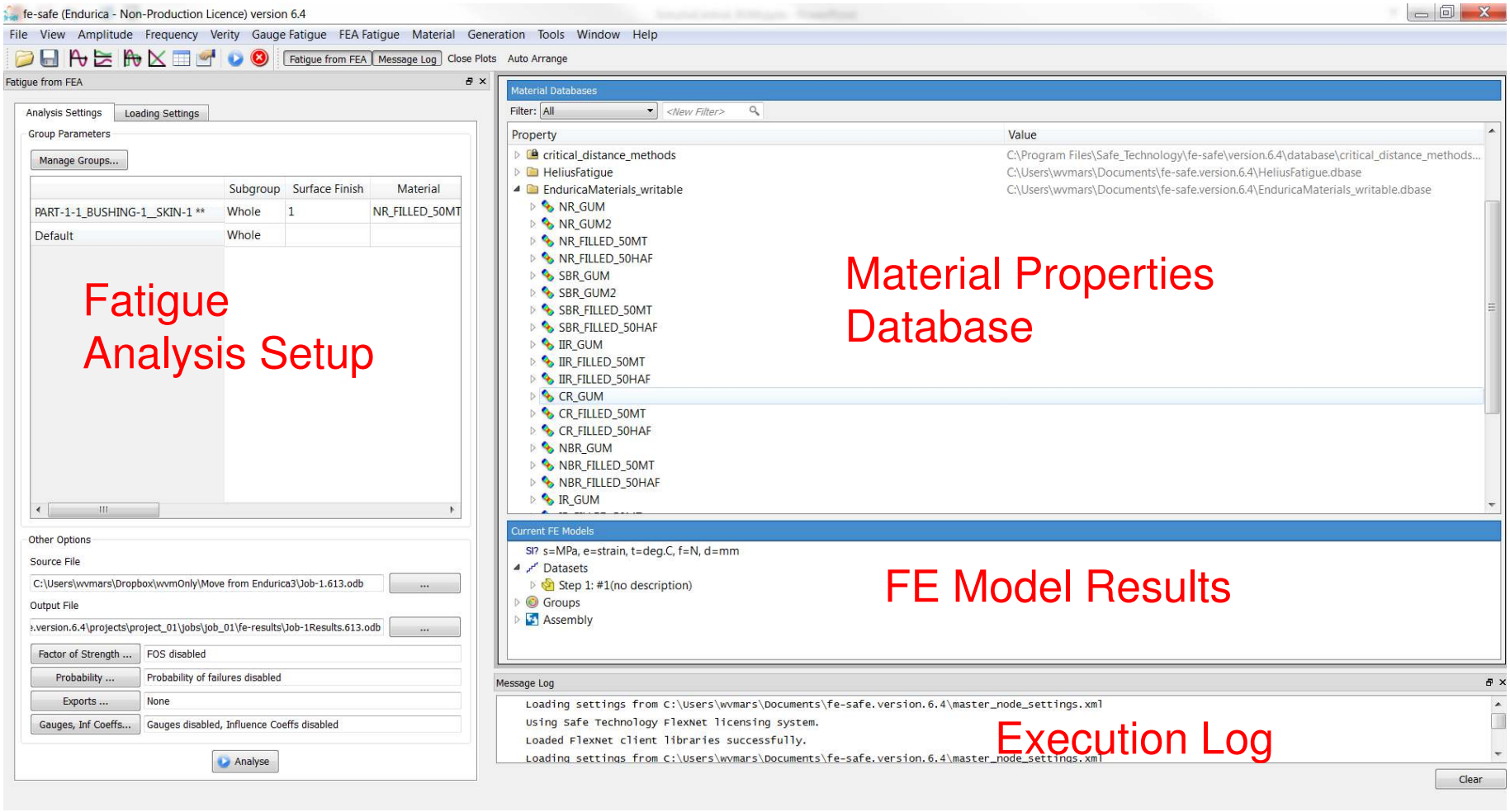
Fe-safe/Rubber fatigue analysis software



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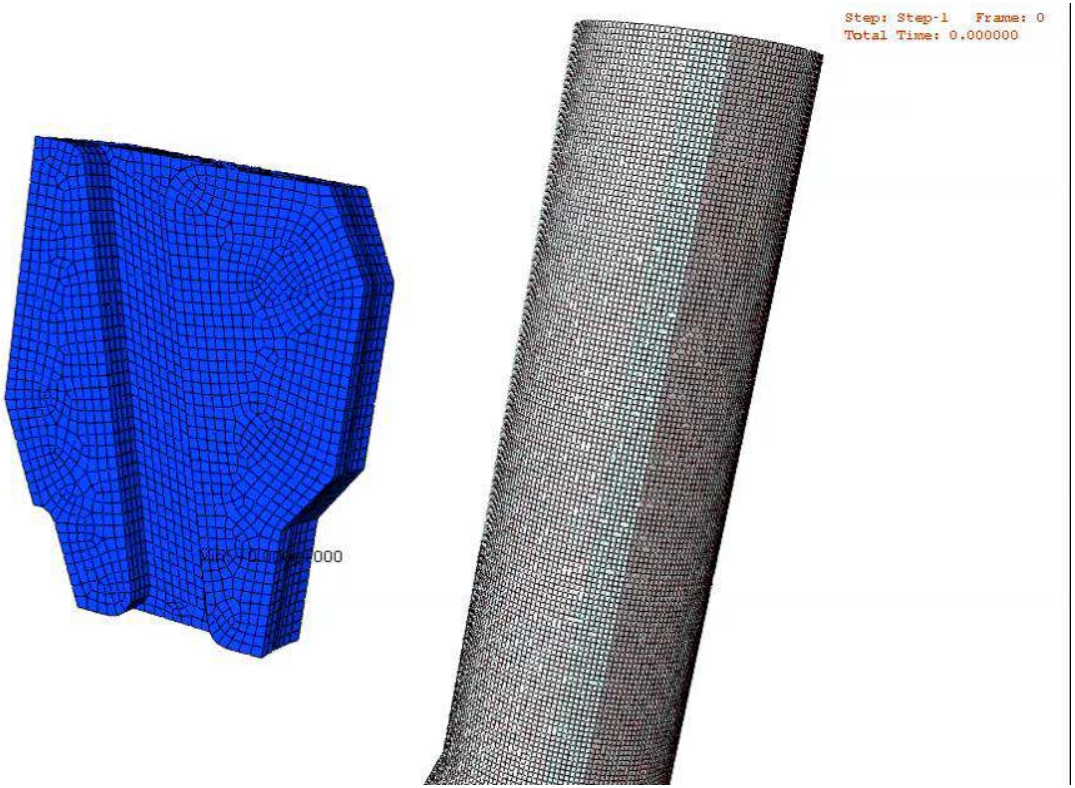
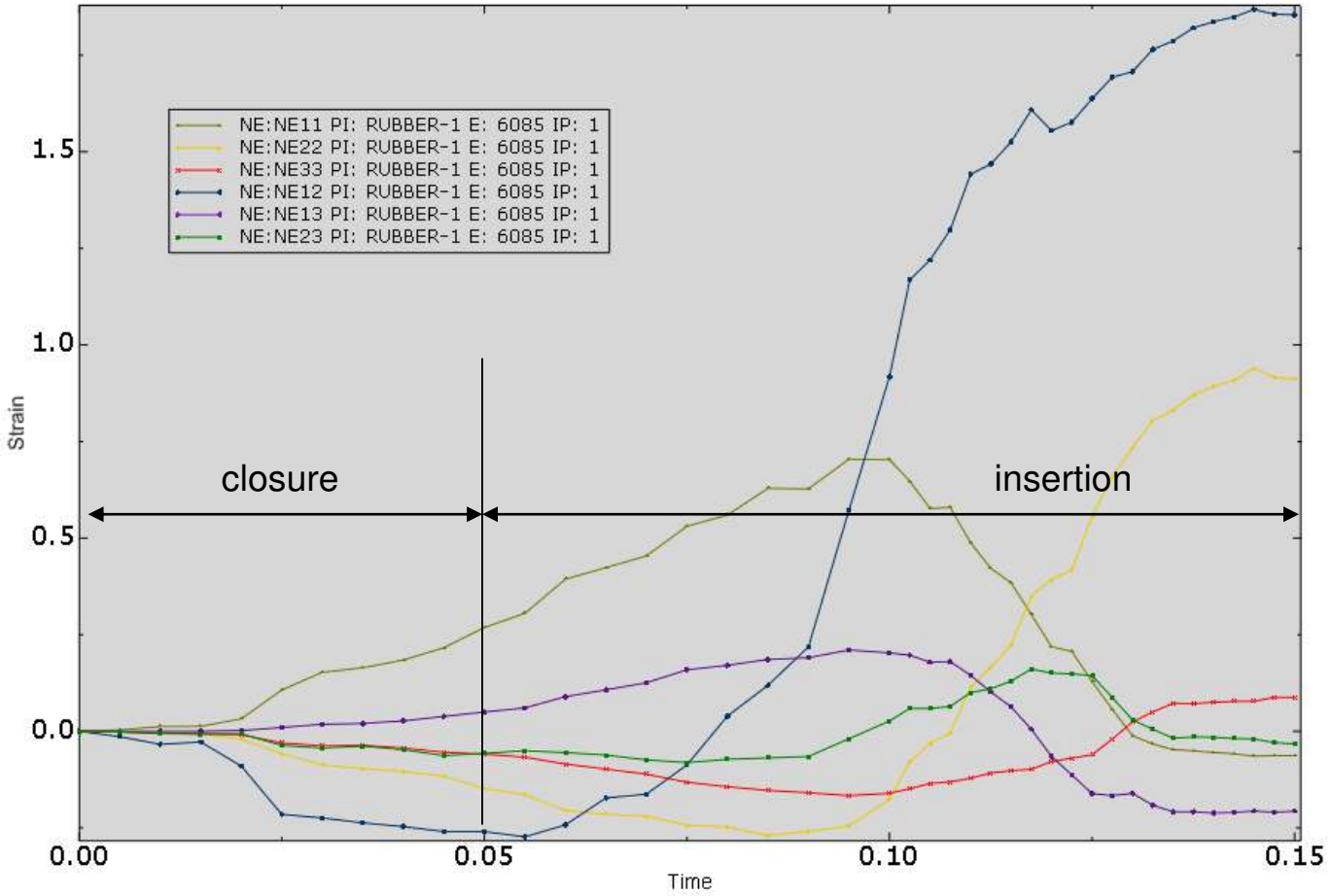
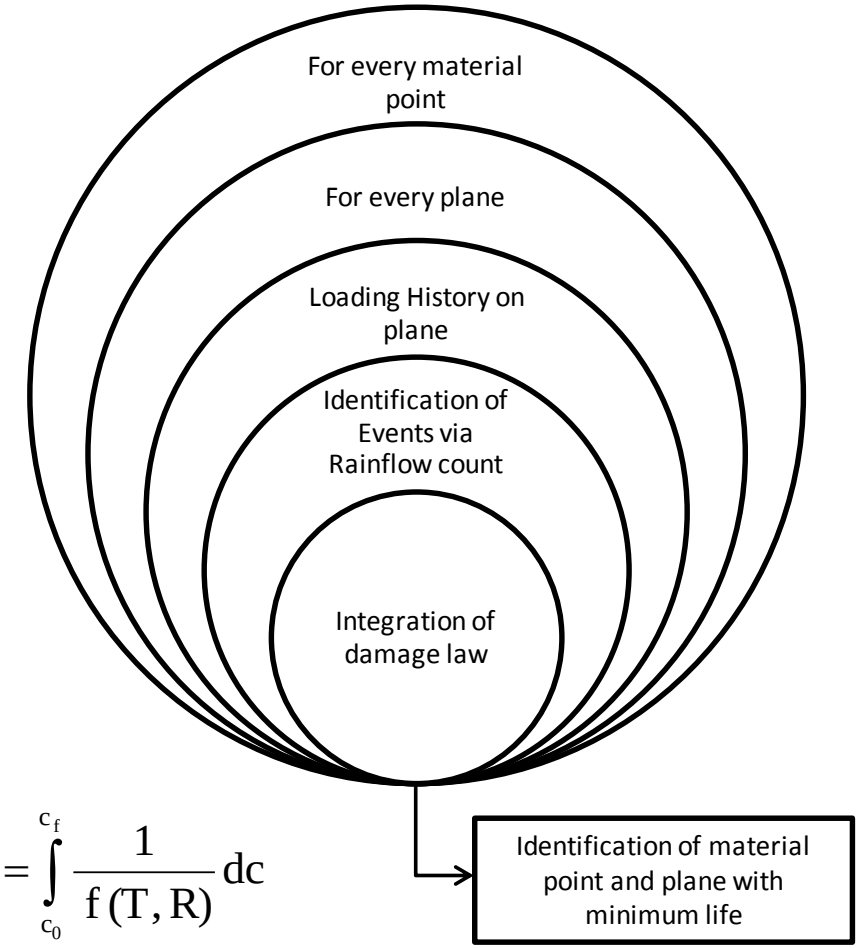
FE Analysis of sealing element



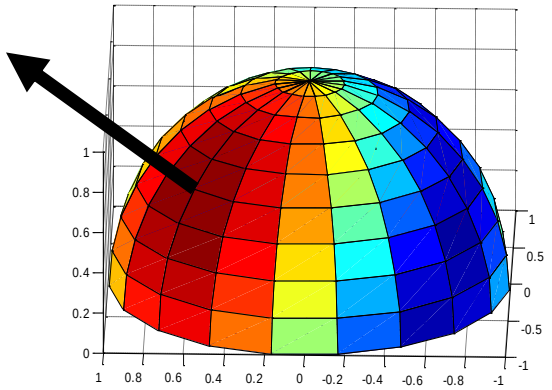
Strain History: worst element 6085



Technology: Critical Plane Analysis



$$N_f(\theta,\phi) = \int_{c_0}^{c_f} \frac{1}{f(T,R)}\,dc$$



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

US Patent No. 6,634,236 B1

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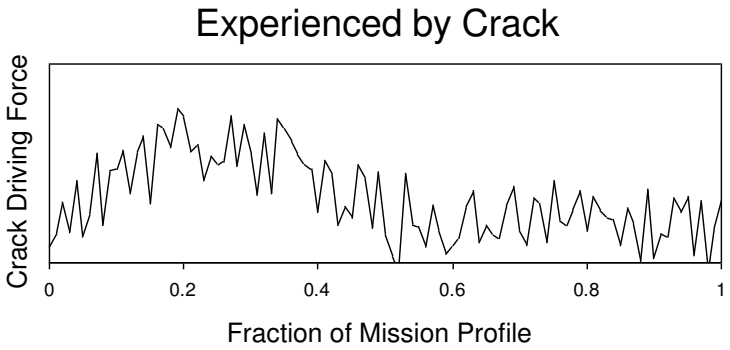
Technology: Damage accumulation



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

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

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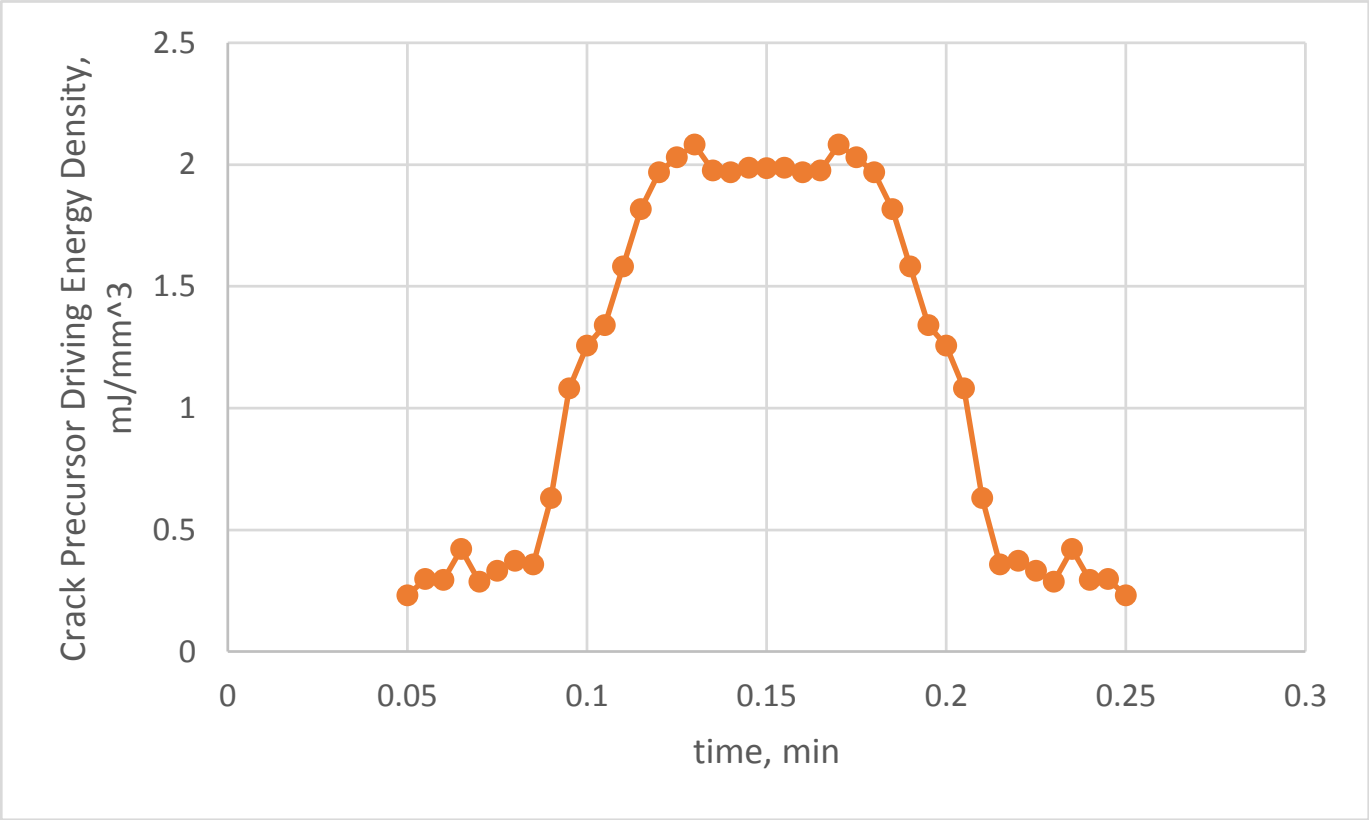
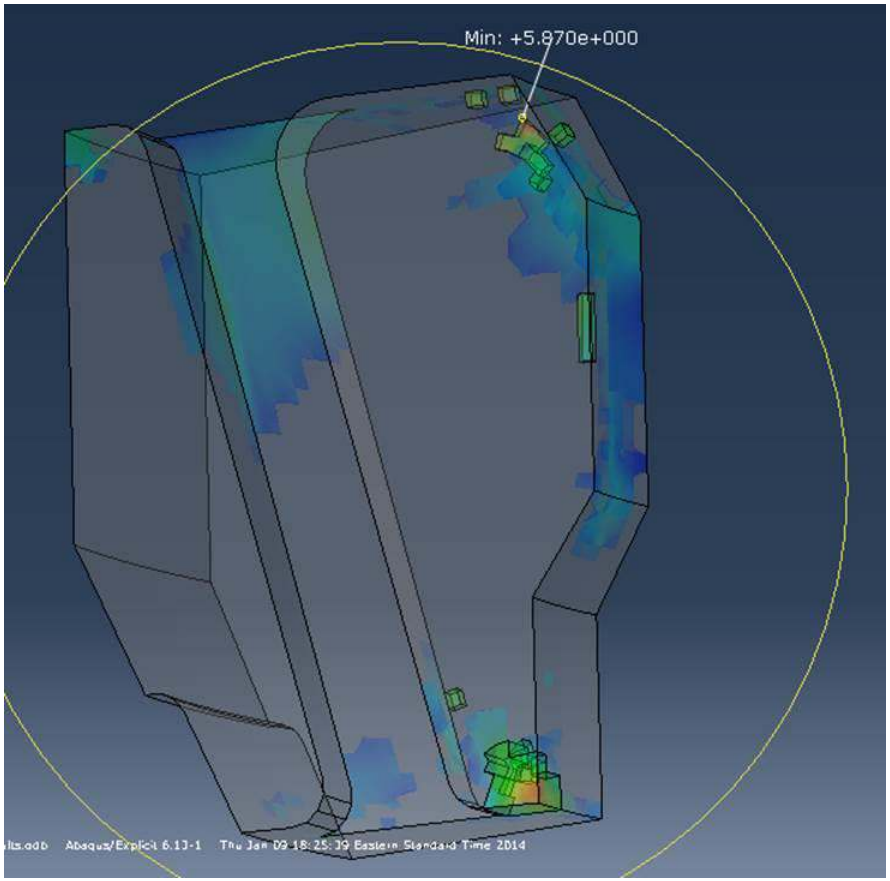
Crack Precursor Driving Energy Density, worst element



Fatigue Life of Sealing Element



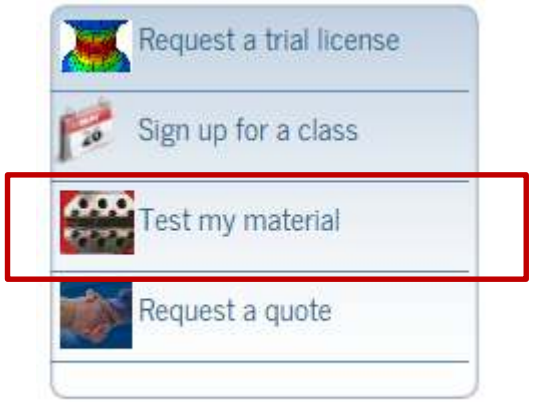
N=5870

Forward paths:

- Materials A vs B
- Pipe diameter effects
- Control recommendations for control on ID

Forward Paths…

•18-20 Feb : Characterizing elastomer fatigue behavior for analysis & engineering, (Ann Arbor, USA)
•22 – 24 July: Theory & Application of Rubber Fatigue Analysis (Houston, TX, USA)



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fe-safe/Rubber™

Mark Wyatt
North American Sales, 3DS
Office: 781 810 3759
mark.wyatt@3ds.com

Henry Gonzalez
Senior Sales Representative
3DS
281 827 8745

SIMULIA

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