



Durability Analysis of Uniaxial & Biaxial Inputs to Elastomeric Front Lower Control Arm Vertical Ride Bushing

Presented at fe-safe UGM on October 19th, 2016

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Endurica LLC: Will Mars, Jesse Suter, & Mark Bauman

Presentation Agenda



1. Who is Tenneco & how do we use fe-safe/Rubber
2. Overview of fe-safe/Rubber fatigue prediction software
3. Tenneco material testing capabilities for fe-safe/Rubber
4. Abaqus & fe-safe/Rubber methodology
5. Results of predictive Analysis to Bench Durability
6. Questions



TENNECO

Walker Division

Integrated Exhaust Systems,
Catalytic Converters

Founded 1908



Monroe Division

Passive & Active Shock
Absorbers, Struts

Founded 1916



Clevite Division

Suspension Links, Bushings,
Isolators, Mounts

Founded 1933



- Tenneco is an early adopter of fe-safe/Rubber as a tool to optimize the design of our products and to minimize engineering risk associated with meeting application durability requirements.
- Our OEM customers require durability predictions during the technical review stage prior to quoting on new business.
 - Our OEM's expect Tenneco to be able to take block cycle test conditions and verify that a proposed design will exceed the durability requirements with statistical confidence.

fe-safe\Rubber material testing modules from Endurica



Hyperelastic Module

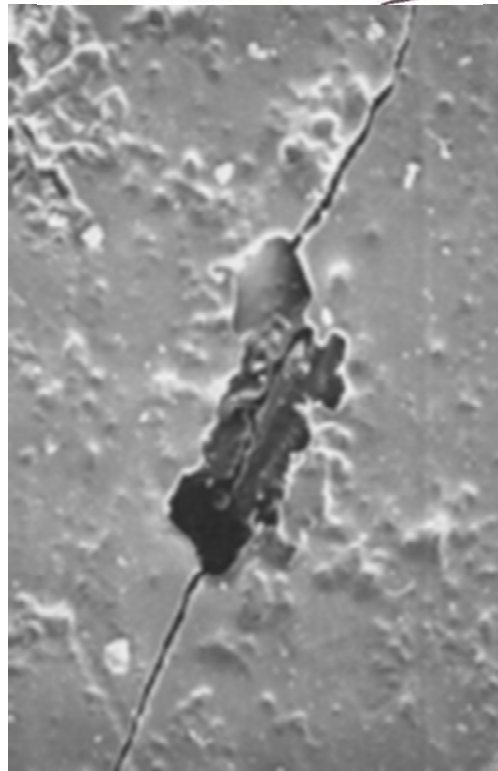
Simple, Planar, and Equibiaxial tension, Mullins Effect

Core Fatigue Module

Fully Relaxing Behavior from both nucleation and fracture mechanical perspectives

Intrinsic Strength (>10⁶ cycles) Module

Quantify endurance limits



Extended Life (>10⁶ cycles) Module

Quantify endurance limit, estimate aging rate of stiffness, intrinsic and ultimate strength

Thermal Module

Quantify dissipative properties, thermal properties, temperature dependence

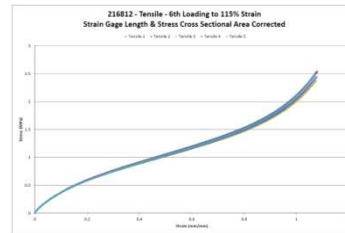
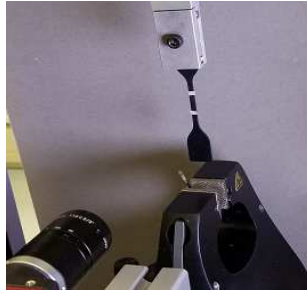
Nonrelaxing Module

Quantify Strain Crystallization, Min and Mean Strain Effects

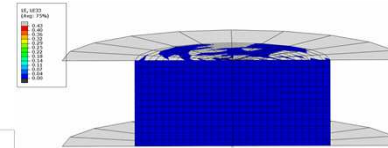
Hyperelastic Testing – Simple, Planar, Equalbiaxial Tensions, Bulk Modulus, & Simple Compression



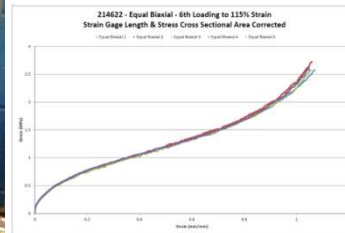
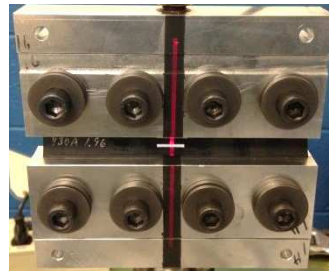
Uniaxial Tension testing being measured with a Video Extensometer



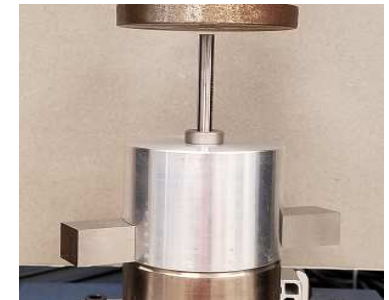
Simple Compression testing for correlations between real world and FEA modeling



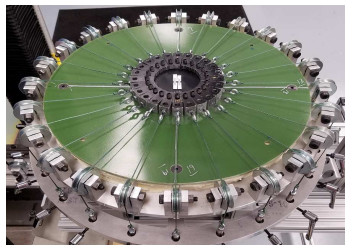
Planar Tension testing for Pure Shear analysis via Laser Extensometer



Volumetric Compression testing confines elastomeric buttons volumetrically resulting in Bulk Modulus



Equibiaxial Extension testing for measure compression characteristics of elastomers



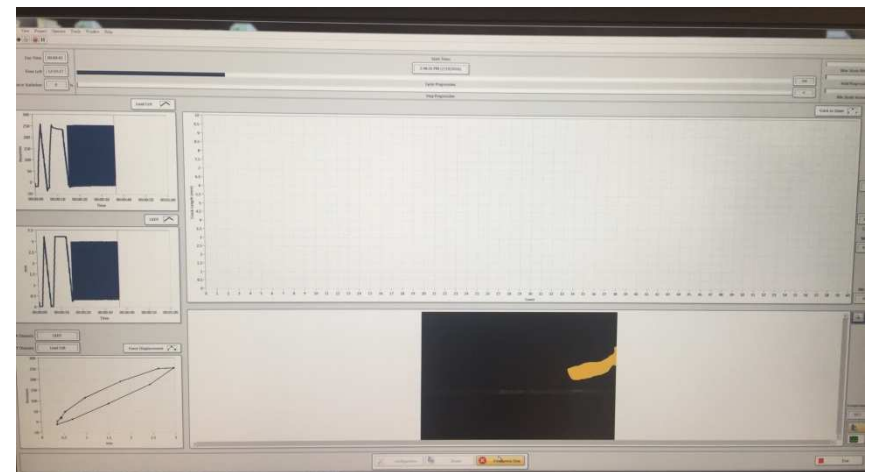
Core Fatigue Fully Relaxing & Nonrelaxing Modules



- **Fatigue Crack Growth (FCG) testing to obtain the crack growth rate verses the crack propagation energy elastomeric compounds.**



Advanced Vision Systems are utilized to capture the crack growth between fatigue cycles.



MTS 832 used with NI Labview Software Is used to control and output data for the Fatigue Crack Growth Analysis.



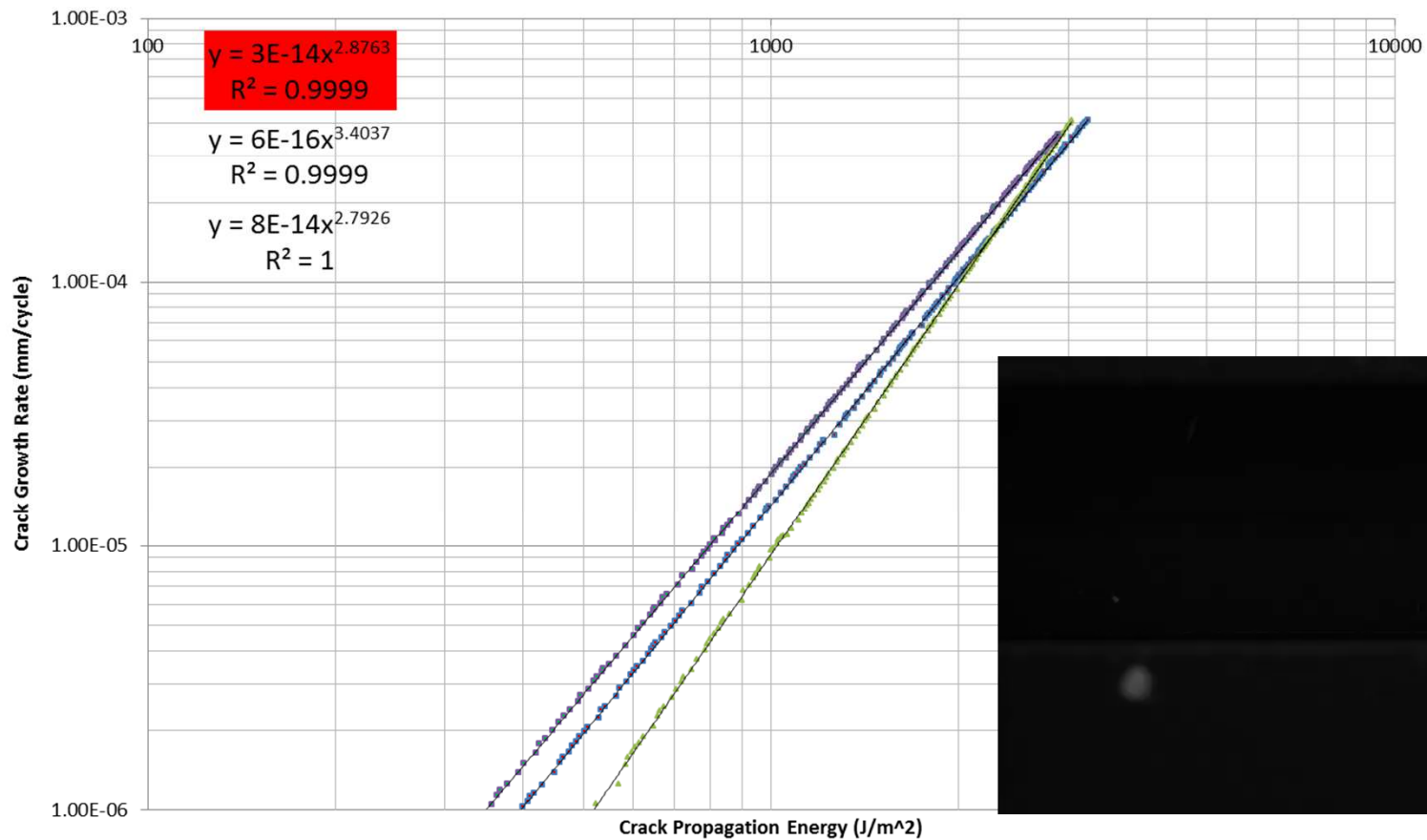
Tenneco along with an outside software development firm created the software package to accurately monitor and calculate the crack growth as well as all the pertaining physical characteristics attributed to crack growth of a planar tension specimen.

FCG FR – Lake/Lindley Model



Crack Growth vs Crack Propagation Energy

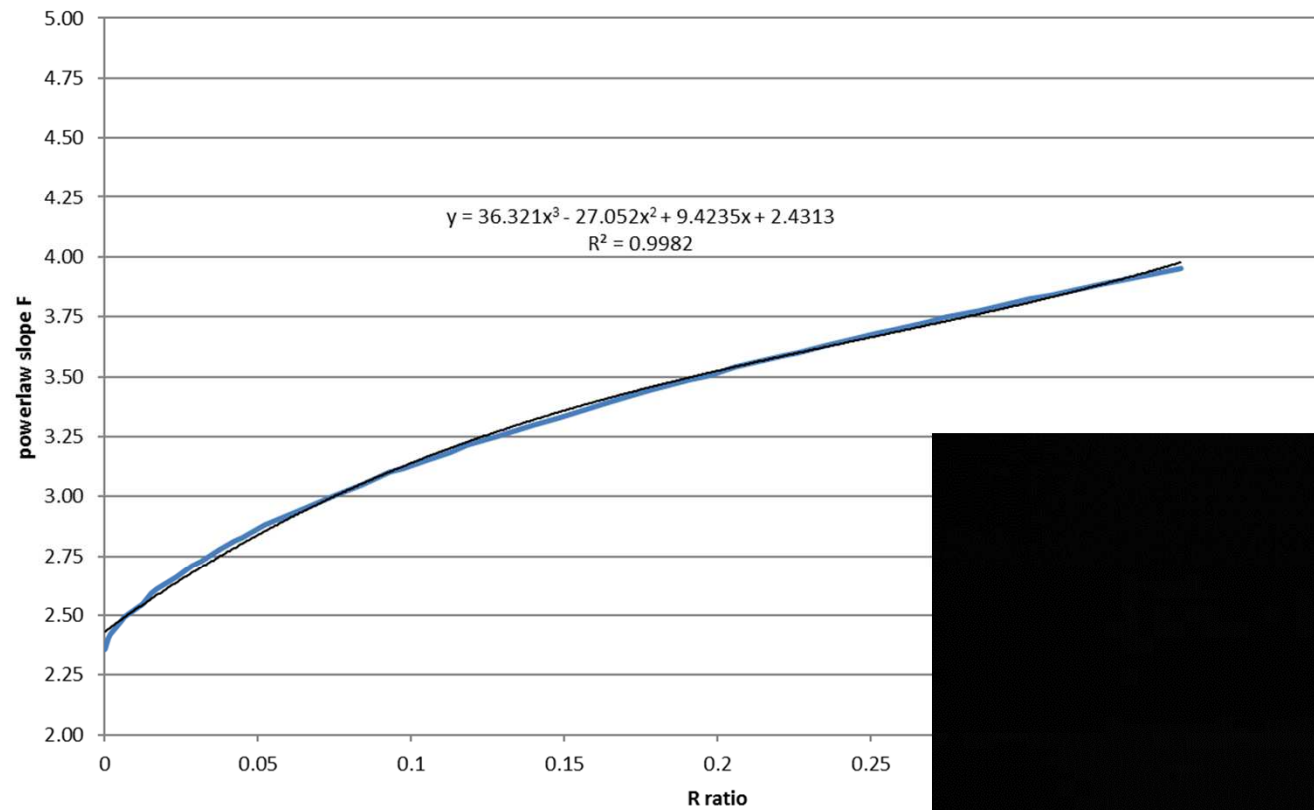
- FCG-1 - 01JP146A - Tenneco - 24 Hr Precut #46, 10 Hz - FR
- FCG-2 - 01JP146A - Tenneco - 24 Hr Precut #45, 10 Hz - FR
- FCG-3 - 01JP146A - Tenneco - 24 Hr Precut #44, 10 Hz - FR
- Power (FCG-1 - 01JP146A - Tenneco - 24 Hr Precut #46, 10 Hz - FR)
- Power (FCG-2 - 01JP146A - Tenneco - 24 Hr Precut #45, 10 Hz - FR)
- Power (FCG-3 - 01JP146A - Tenneco - 24 Hr Precut #44, 10 Hz - FR)



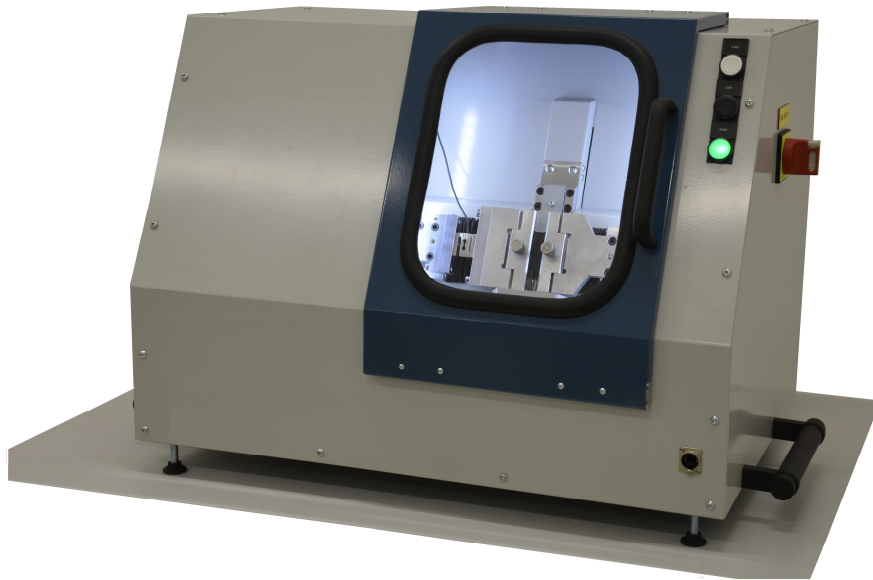
FCG NR – Mars/Fatemi Model



FCG NR - 54% Max Strain

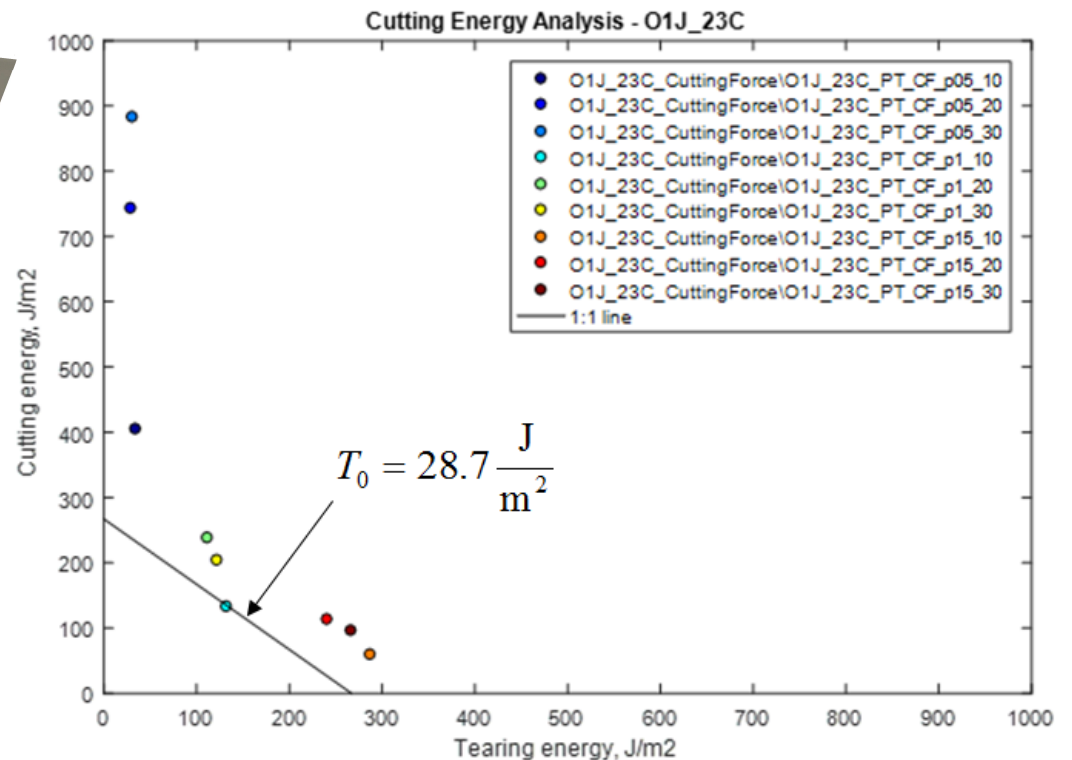


Intrinsic Strength

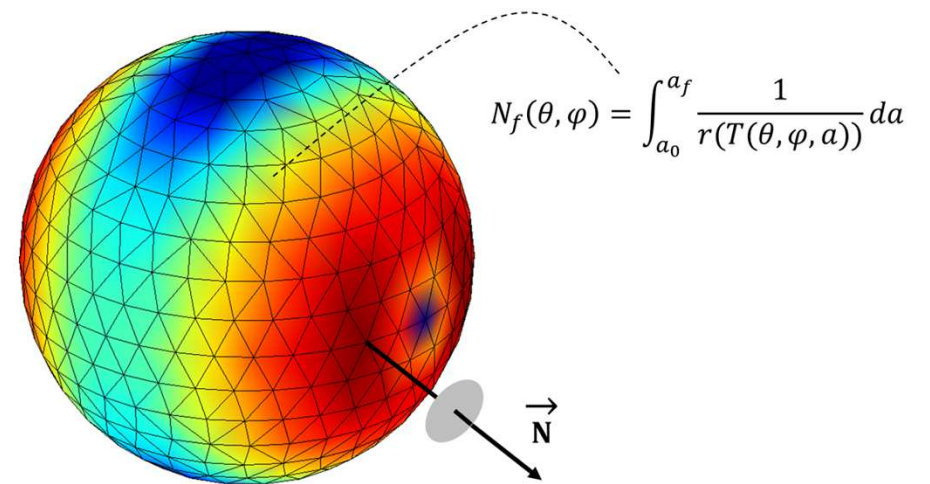
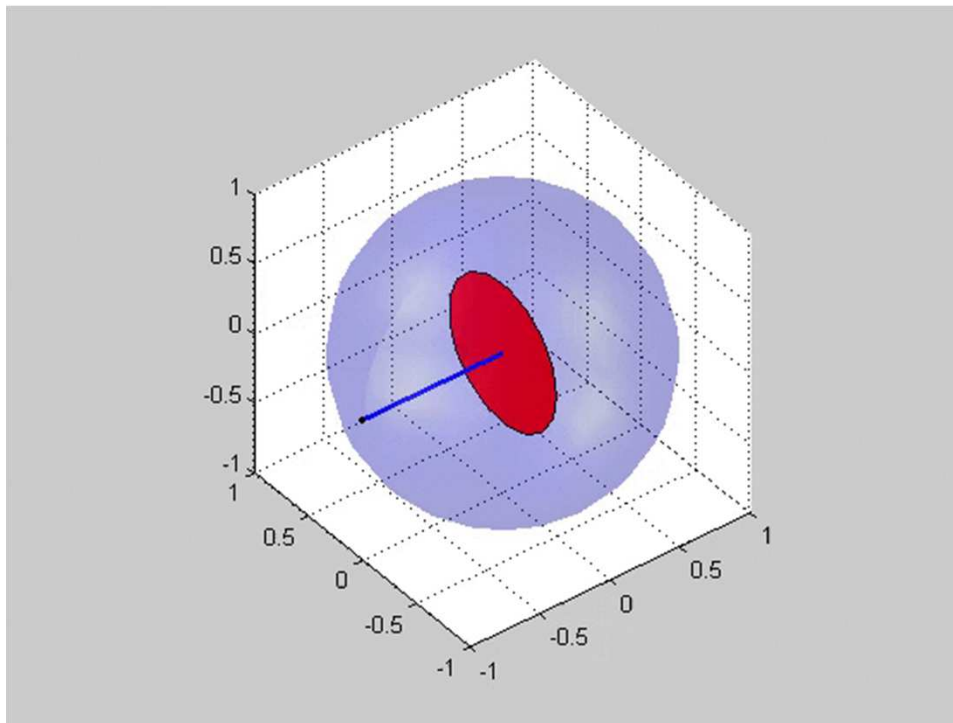


Off the shelf test instrument available through Endurica LLC, for performing cutting force measurements on planar tension specimen using 5nm diamond knife.

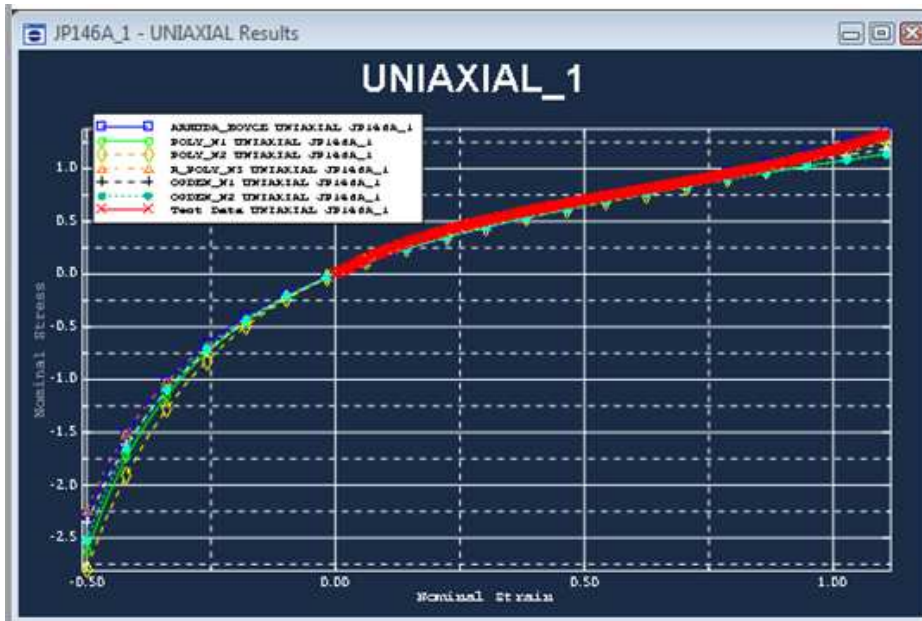
Chart shows results of cutting force measurements. Value is correlated to the test result of minimum cutting energy as a worst case value.



Fatigue Life Calculation: Critical Plane



Summary of Material Input Deck



Material: JP146A
Job Name: JP146A_2

- Polynomial, N = 1 (Mooney-Rivlin)
- Polynomial, N = 2
- Ogden, N = 1
- Ogden, N = 2
- Reduced Polynomial, N = 3 (Yeoh)
- Arruda-Boyce

HYPERELASTICITY - OGDEN STRAIN ENERGY FUNCTION WITH N = 2

I	MU_I	ALPHA_I	D_I
1	0.668199767	1.57397378	9.418022469E-04
2	2.634342322E-02	-3.41338039	7.721885092E-05

STABILITY LIMIT INFORMATION

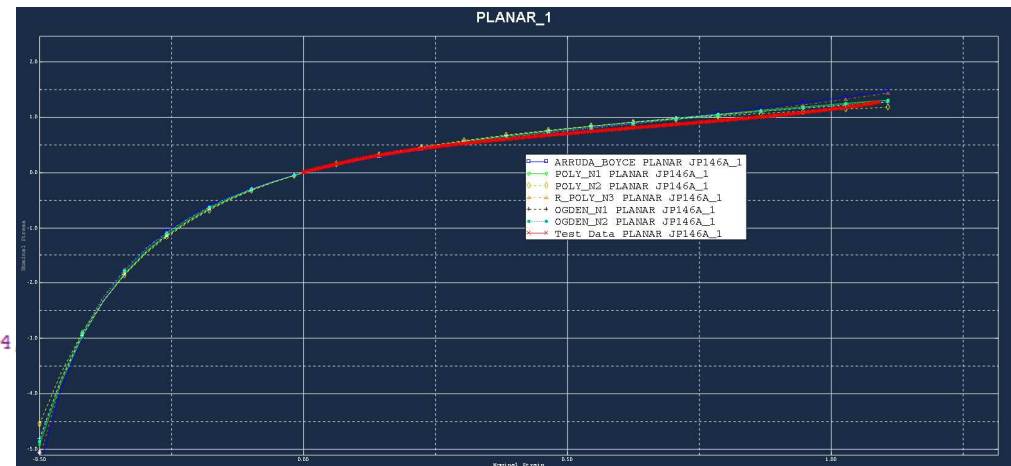
UNIAXIAL TENSION: STABLE FOR ALL STRAINS
 UNIAXIAL COMPRESSION: STABLE FOR ALL STRAINS
 BIAXIAL TENSION: STABLE FOR ALL STRAINS
 BIAXIAL COMPRESSION: STABLE FOR ALL STRAINS
 PLANAR TENSION: STABLE FOR ALL STRAINS
 PLANAR COMPRESSION: STABLE FOR ALL STRAINS
 VOLUMETRIC TENSION: STABLE FOR ALL VOLUME RATIOS
 VOLUMETRIC COMPRESSION: STABLE FOR ALL VOLUME RATIOS

115% - ST, PT, EBE, & VC

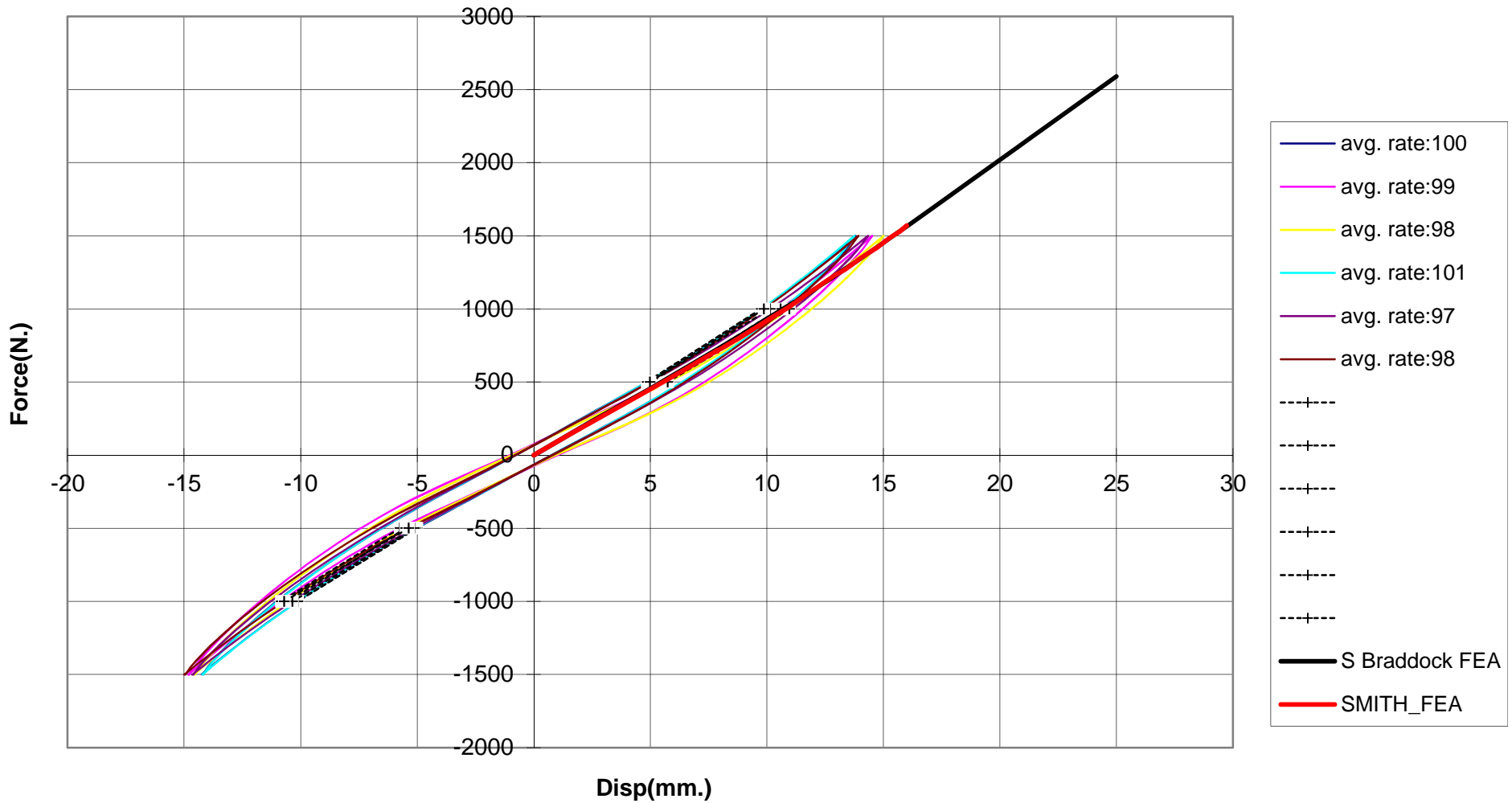
85% - ST, PT, EBE, & VC

```

** MATERIALS
**
*Material, name=Rubber_45
*Density
  1.1e-09,
*Expansion
  0.0001429,
*HYPERELASTIC, ogden, n=2
0.668199767, 1.57397378, 2.634342322E-02, -3.41338039, 9.418022469E-04
**
** BOUNDARY CONDITIONS
**
** Name: BC-1-RP Type: Displacement/Rotation
    
```



Axial Force vs. Displacement - FEA Correlation vs. Testing



fe-safe/Rubber – Material Definitions



Material Databases

Filter: All <New Filter> Launch external database

Property	Value
hyperelastic : ARRUDABOYCE SHEAR_MODULUS (MPa)	Unused
hyperelastic : MOONEYRIVLIN BULK_MODULUS (MPa)	Unused
hyperelastic : MOONEYRIVLIN C01 (MPa)	Unused
hyperelastic : MOONEYRIVLIN C10 (MPa)	Unused
hyperelastic : NEOHOOKEAN BULK_MODULUS (MPa)	Unused
hyperelastic : NEOHOOKEAN C10 (MPa)	Unused
hyperelastic : OGDEN ALFA1	1.574
hyperelastic : OGDEN ALFA2	-3.41338
hyperelastic : OGDEN ALFA3	Unused
hyperelastic : OGDEN ALFA4	Unused
hyperelastic : OGDEN ALFA5	Unused
hyperelastic : OGDEN ALFA6	Unused
hyperelastic : OGDEN D1 (1/MPa)	.0009418
hyperelastic : OGDEN D2 (1/MPa)	7.7219e-05
hyperelastic : OGDEN D3 (1/MPa)	Unused
hyperelastic : OGDEN D4 (1/MPa)	Unused
hyperelastic : OGDEN D5 (1/MPa)	Unused
hyperelastic : OGDEN D6 (1/MPa)	Unused
hyperelastic : OGDEN MU1 (MPa)	0.6682
hyperelastic : OGDEN MU2 (MPa)	.0263434

Material Databases

Filter: All <New Filter> Launch external database

Property	Value
fcgr : Type	LAKELINDLEY
fcgr : c0 (mm)	.025
fcgr : cf (mm)	1
fcgr : F0	2.3977
fcgr : rc (mm/cyc)	.0048
fcgr : T0 (kJ/m^2)	.029
fcgr : Tc (kJ/m^2)	9.2
fcgr : TempCoef (1/degC)	0.0061
fcgr : TempRef (degC)	20
fcgr : Tt (kJ/m^2)	.49
fcgr : fcgr(T) (mm/cyc)	Unused
e-cryst : Type	MARFATEMI
e-cryst : F1	16.329
e-cryst : F2	-24.807
e-cryst : F3	20.333
e-cryst : Fexp	0.0
e-cryst : x(R)	0, 0.256574005, 0.338849992, 0.397762001, 0.445037991, 0.4850...
ccgr : Type	NOCREEP
ccgr : FQS	Unused
ccgr : RQS (mm/sec)	Unused

Current FE Models

SI? s=MPa, e=strain, t=deg.C, f=N, d=mm

- Datasets
 - File [I:\abawork\98sox_endurica_axial_48_20mm_cax4h_penalty_s2s_refine1.odb]
 - Step 1 : LOAD CASE 1 TEMPERATURE COOL DOWN
 - Step 2 : LOAD CASE 2 EXTERNAL SWAGE & IT DRIFT
 - Step 3 : Load to Peak Axial
 - Increment 0 (Time 0) to Increment 99 (Time 0.777557)
 - Increment 100 (Time 0.777564) to Increment 160 (Time 1)
 - Step 4 : Return to Zero
- Groups
- Assembly

fe-safe/Rubber – Establishing Strain History



NE, Max

Current FE Models

SI? s=MPa, e=strain, t=deg.C, f=N, d=mm

- ▲ Datasets
 - ▲ File [I:\abawork\98xx_endurica_axial_48_20mm_cax4h_penalty_s2s_refine1.odb]
 - ▲ Step 1 : LOAD CASE 1 TEMPERATURE COOL DOWN
 - ▶ Increment 0 (Time 0)
 - ▶ Increment 1 (Time 0.2)
 - ▶ Increment 2 (Time 0.4)
 - ▶ Increment 3 (Time 0.7)
 - ▶ Increment 4 (Time 1)
 - ▲ Step 2 : LOAD CASE 2 EXTERNAL SWAGE & IT DRIFT
 - ▶ Increment 0 (Time 0)
 - ▶ Increment 1 (Time 0.1)
 - ▶ Increment 2 (Time 0.2)
 - ▶ Increment 3 (Time 0.35)
 - ▶ Increment 4 (Time 0.575)
 - ▶ Increment 5 (Time 0.9125)
 - ▶ Increment 6 (Time 1)
 - ▲ Step 3 : Load to Peak Axial
 - ▶ Increment 0 (Time 0) to Increment 99 (Time 0.777557)
 - ▶ Increment 100 (Time 0.777564) to Increment 160 (Time 1)
 - ▲ Step 4 : Return to Zero
 - ▶ Increment 0 (Time 0)
 - ▶ Increment 1 (Time 0.05)
 - ▶ Increment 2 (Time 0.1)
 - ▶ Increment 3 (Time 0.11875)

NE, Max, In-Plane Principal (Avg: 75%)

NE, Max, In-Plane Principal (Avg: 75%)

NE, Max, In-Plane Principal (Avg: 75%)

Analysis Settings Loading Settings

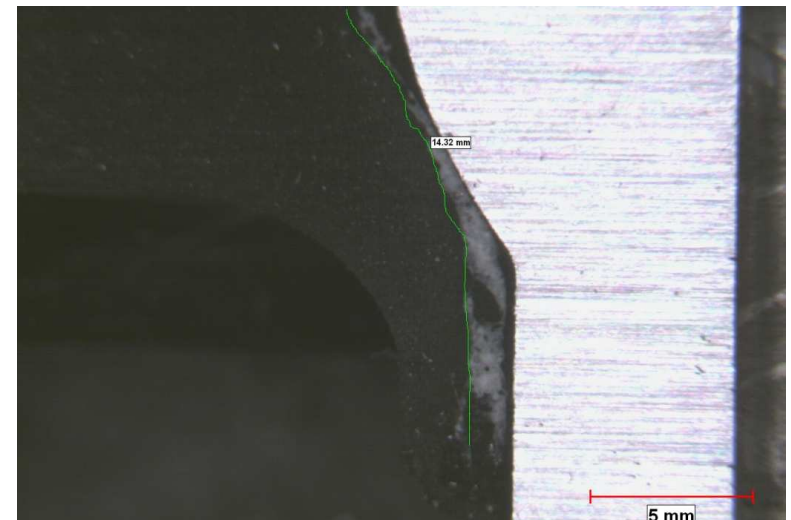
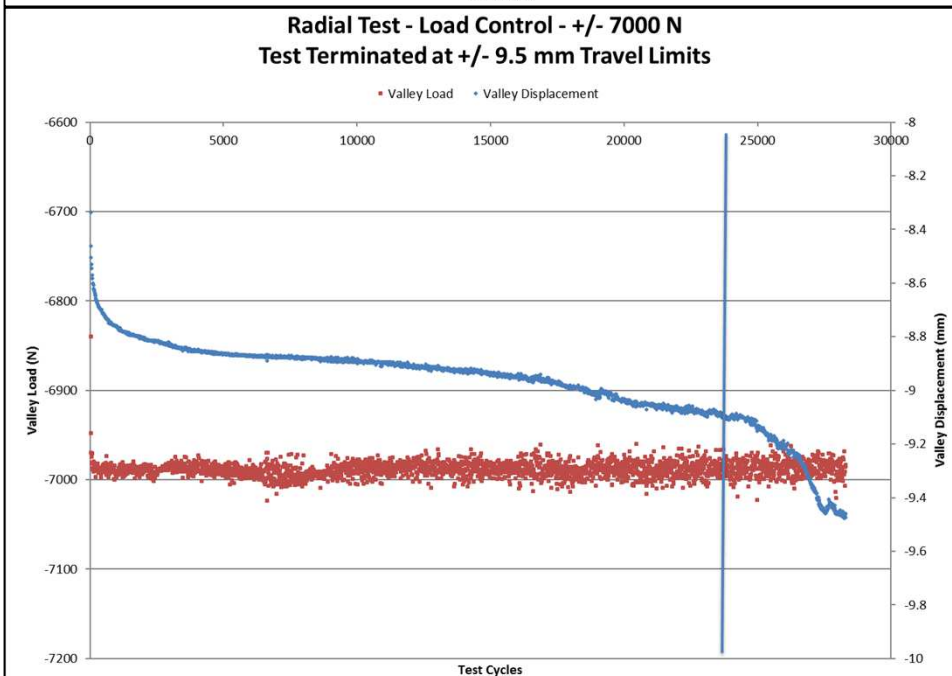
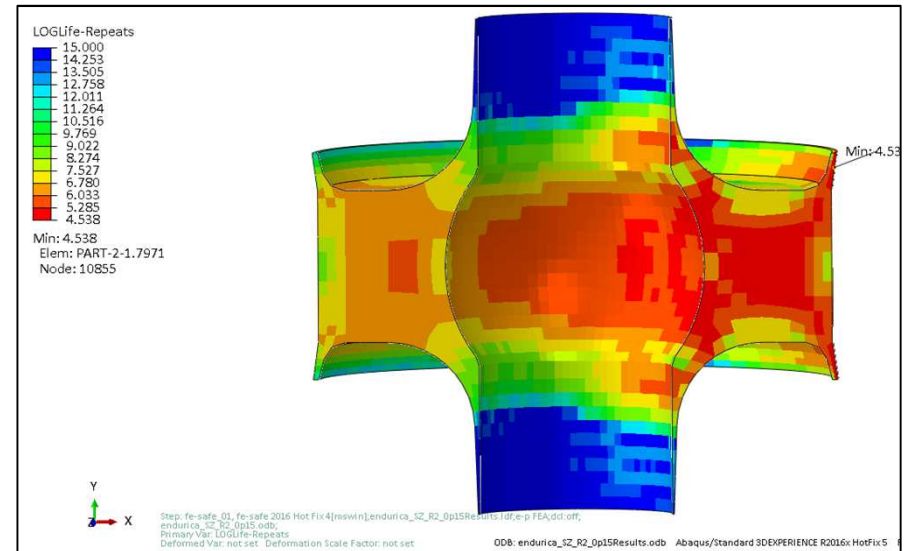
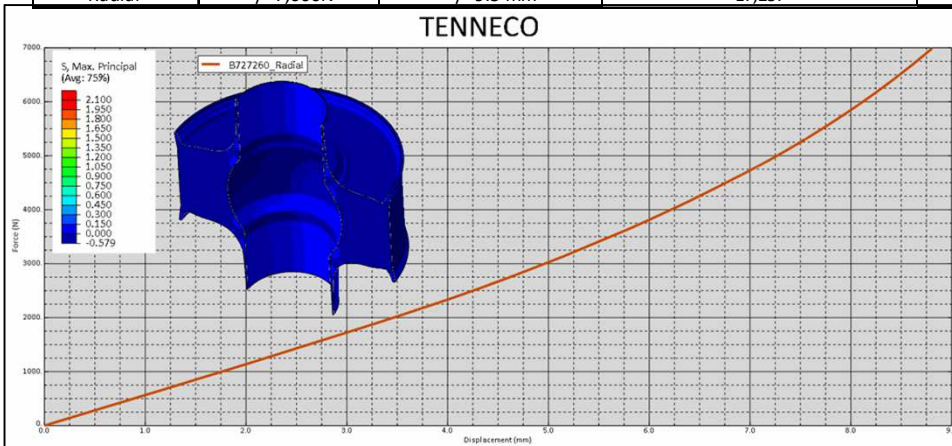
Add...

- Using user profile loading file I:\fe-safe\f...
- ▲ Settings
 - ▶ Loading is equivalent to 1 Repeats
- ▲ Elastic-Plastic Block
 - ▶ Stress Dataset 25-345(2)
 - ▶ Strain Dataset 26-346(2)

fe-safe/Rubber – Radial Summary



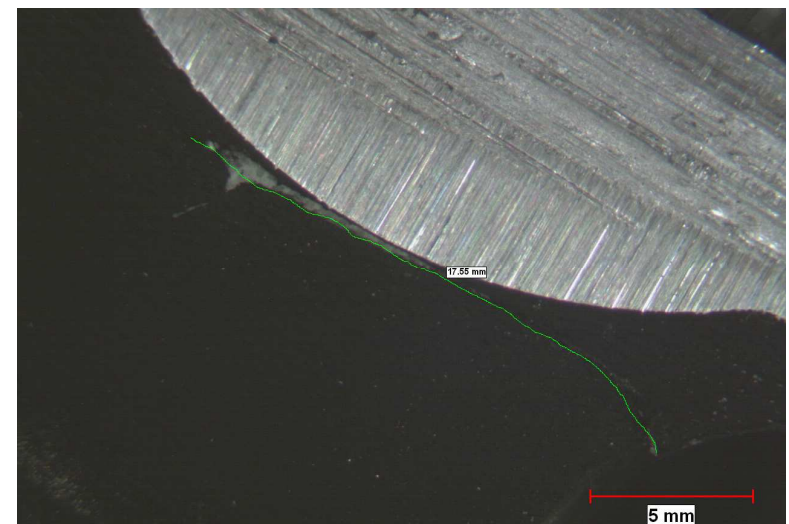
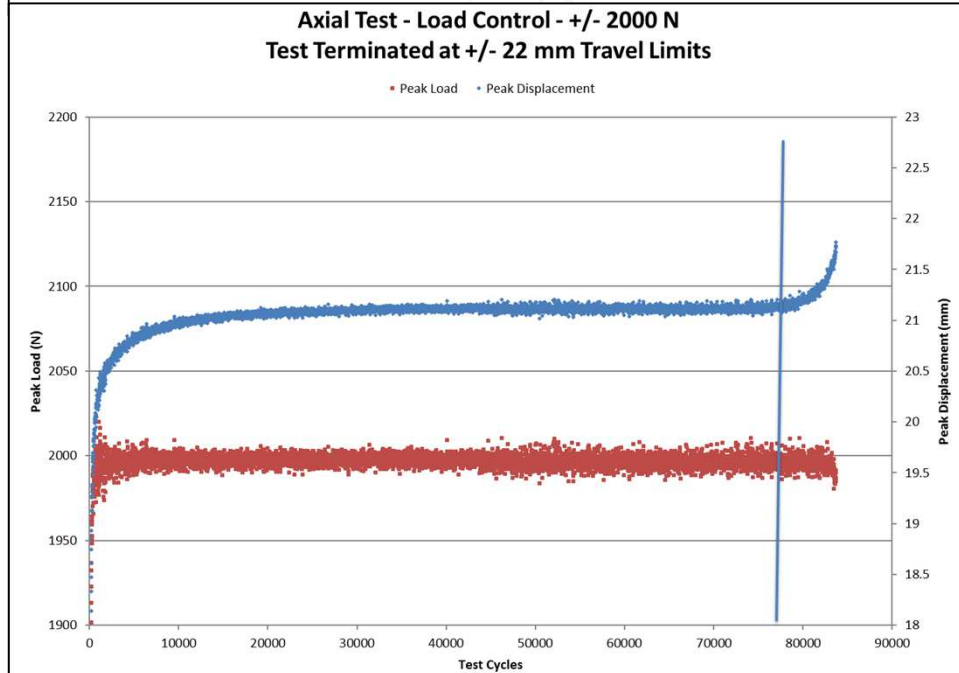
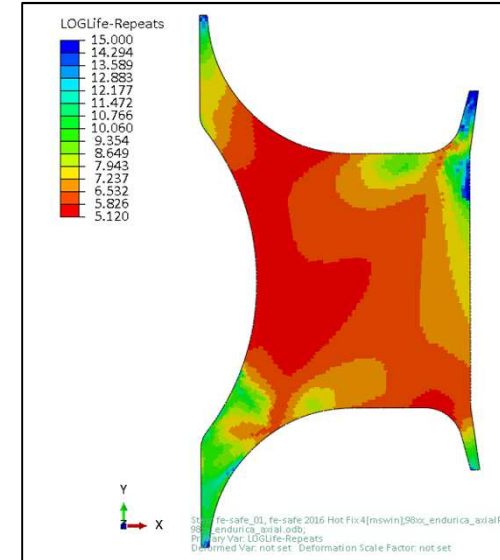
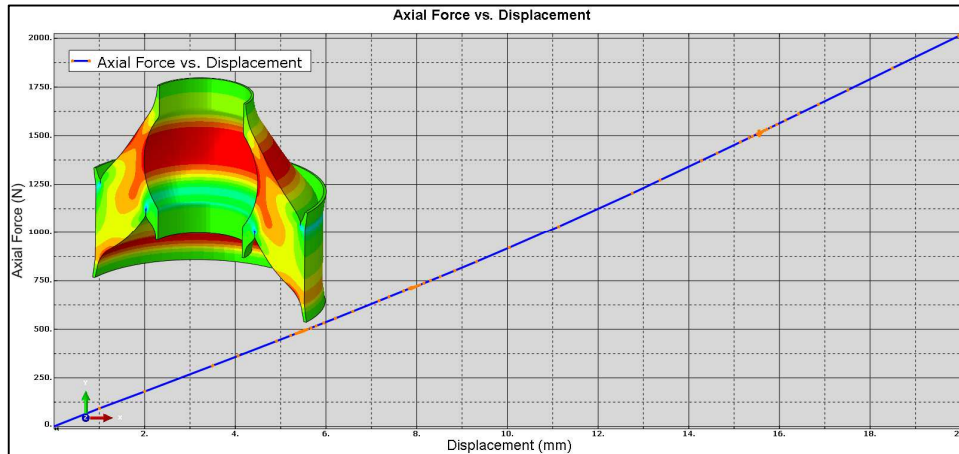
Test Inputs	Test Conditions	Termination Conditions	fe-safe/Rubber Cycles (1 mm Tear)	Cycle of Initial Rate Change	Part Rate Life vs Prediction	Bench Durability Cycles	Tear Length End of Test
Radial	+/- 7,000N	+/- 9.5 mm	17,257	24,132	140%	28,142	14.32 mm



fe-safe/Rubber – Axial Summary



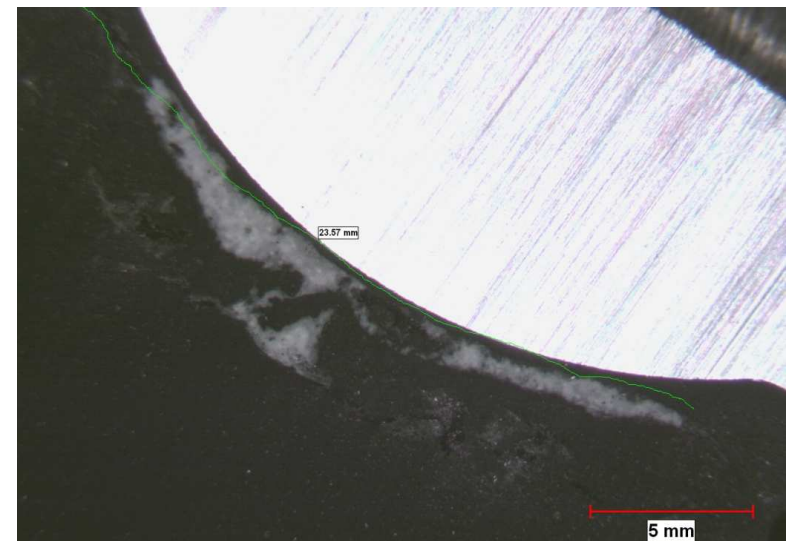
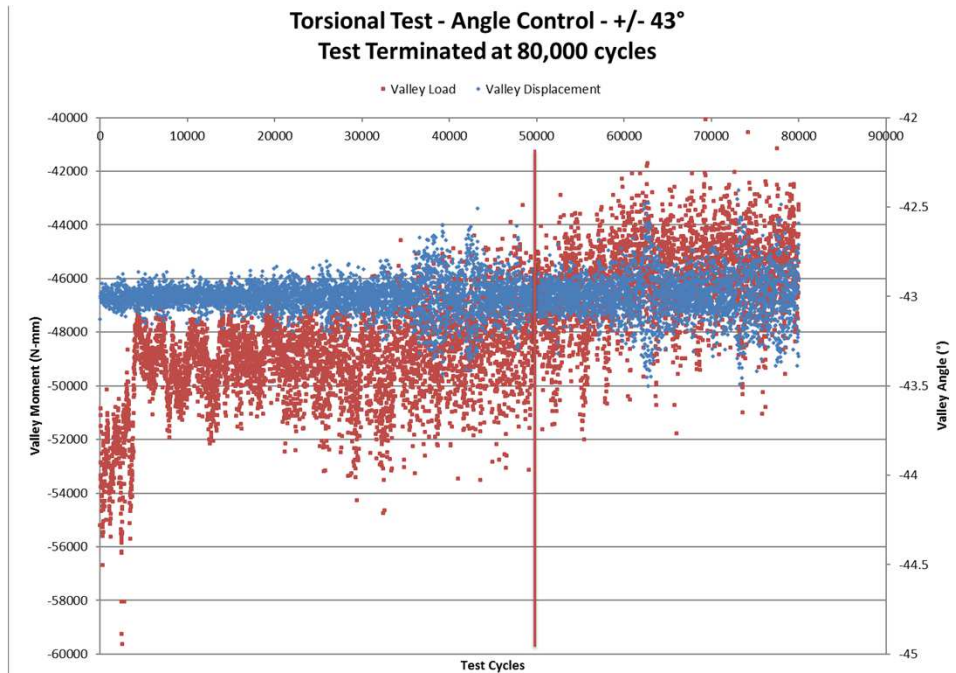
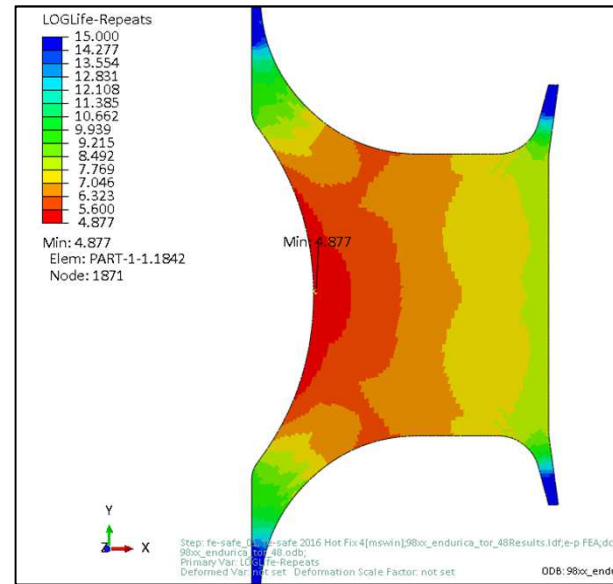
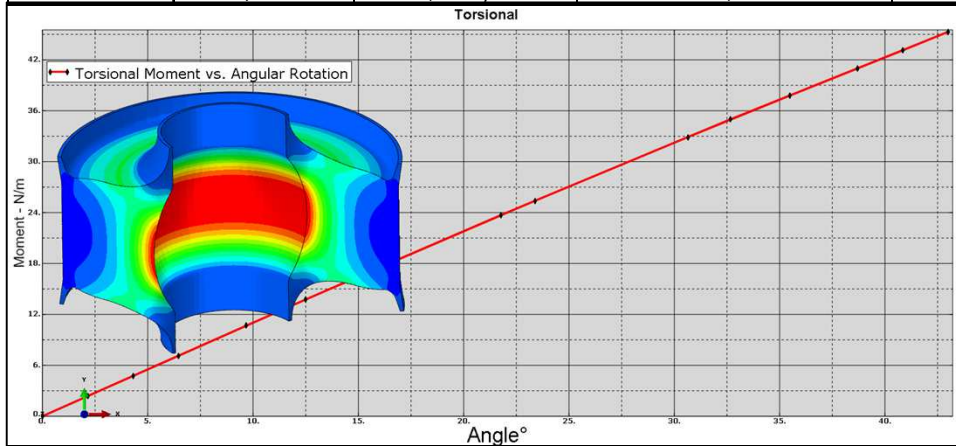
Test Inputs	Test Conditions	Termination Conditions	fe-safe/Rubber Cycles (1 mm Tear)	Cycle of Initial Rate Change	Part Rate Life vs Prediction	Bench Durability Cycles	Tear Length End of Test
Axial	+/- 2,000N	+/-22 mm	65,912	77,275	117%	83,685	17.55 mm



fe-safe/Rubber – Torsional Summary



Test Inputs	Test Conditions	Termination Conditions	fe-safe/Rubber Cycles (1 mm Tear)	Cycle of Initial Rate Change	Part Rate Life vs Prediction	Bench Durability Cycles	Tear Length End of Test
Torsional	+/- 43°	80,000 Cycles	37,668	50,000	133%	79,195	23.57 mm



Radial/Torsional Phase Alignment

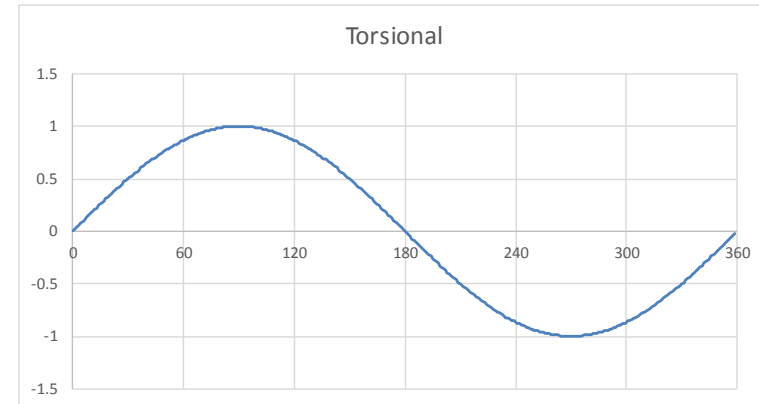
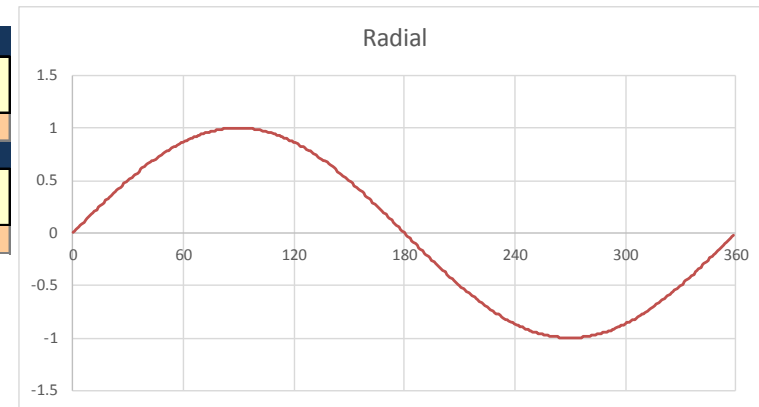


0	0.0000E+00	0	0.0000E+00	0
1	2.7855E-03	0.017	2.7855E-03	0.017452
2	5.5710E-03	0.035	5.5710E-03	0.034899
3	8.3565E-03	0.052	8.3565E-03	0.052336
4	1.1142E-02	0.07	1.1142E-02	0.069756
5	1.3928E-02	0.087	1.3928E-02	0.087156
6	1.6713E-02	0.105	1.6713E-02	0.104528
7	1.9499E-02	0.122	1.9499E-02	0.121869
8	2.2284E-02	0.139	2.2284E-02	0.139173
9	2.5070E-02	0.156	2.5070E-02	0.156434
10	2.7855E-02	0.174	2.7855E-02	0.173648
11	3.0641E-02	0.191	3.0641E-02	0.190809
12	3.3426E-02	0.208	3.3426E-02	0.207912
13	3.6212E-02	0.225	3.6212E-02	0.224951
14	3.8997E-02	0.242	3.8997E-02	0.241922
15	4.1783E-02	0.259	4.1783E-02	0.258819
16	4.4568E-02	0.276	4.4568E-02	0.275637
17	4.7354E-02	0.292	4.7354E-02	0.292372
18	5.0139E-02	0.309	5.0139E-02	0.309017
19	5.2925E-02	0.326	5.2925E-02	0.325568
20	5.5710E-02	0.342	5.5710E-02	0.34202
21	5.8496E-02	0.358	5.8496E-02	0.358368
22	6.1281E-02	0.375	6.1281E-02	0.374607
23	6.4067E-02	0.391	6.4067E-02	0.390731
24	6.6852E-02	0.407	6.6852E-02	0.406737
25	6.9638E-02	0.423	6.9638E-02	0.422618
26	7.2423E-02	0.438	7.2423E-02	0.438371
27	7.5209E-02	0.454	7.5209E-02	0.45399
28	7.7994E-02	0.469	7.7994E-02	0.469472
29	8.0780E-02	0.485	8.0780E-02	0.48481
30	8.3565E-02	0.5	8.3565E-02	0.5

A (Radial)					
Phase Shift	Cycle	Time Step	Amplitude	Frequency (Hz)	Step Time
0	360	2.786E-03	1	1.0	1.000
B (Torsional)					
Phase Shift	Cycle	Time Step	Amplitude	Frequency (Hz)	Step Time
0	360	2.786E-03	1	1.0	1.000

A = Global steps
 B = Time for A
 F = AMP for A
 G = Time for B
 L = AMP for B
 D & I = Repeat interval
 E & K = Reversing Sign

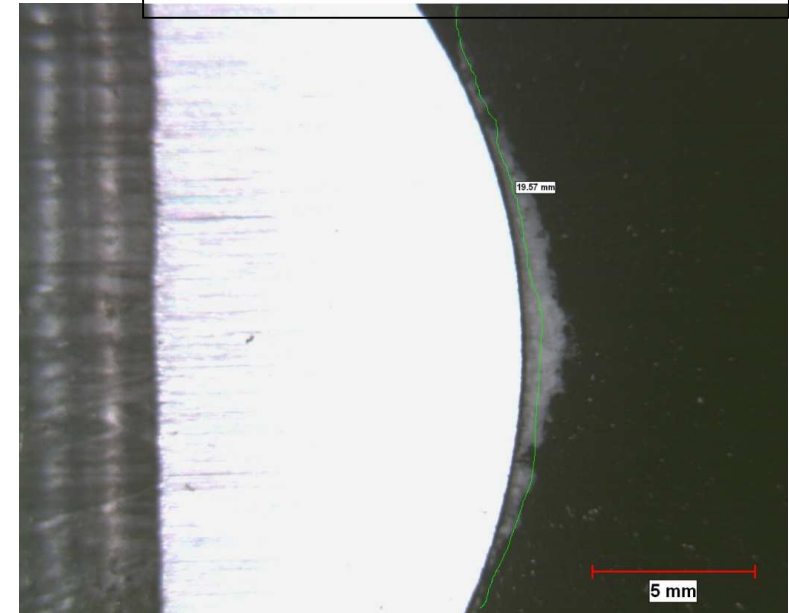
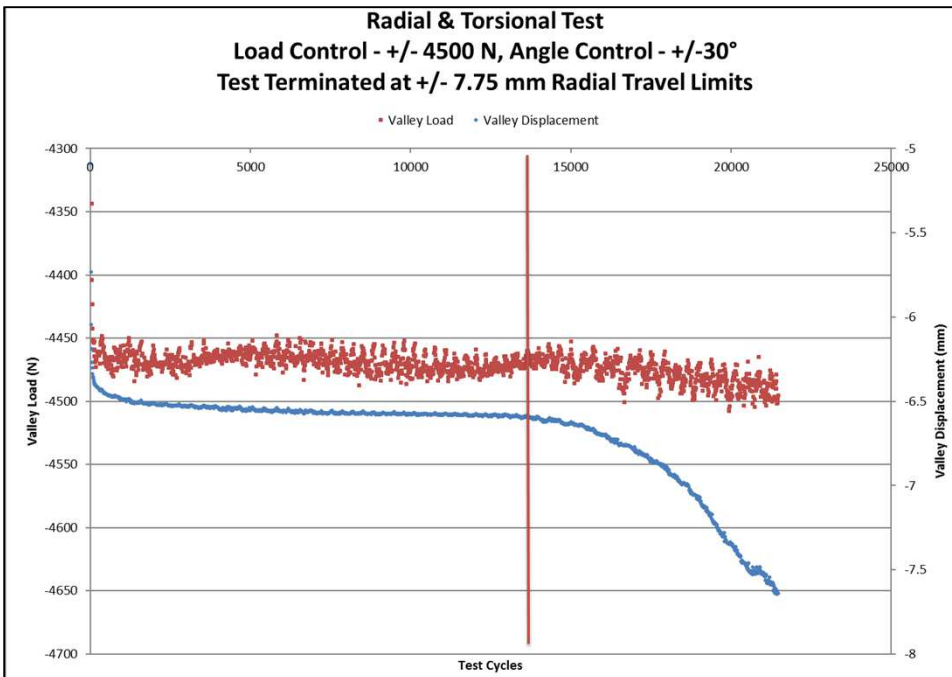
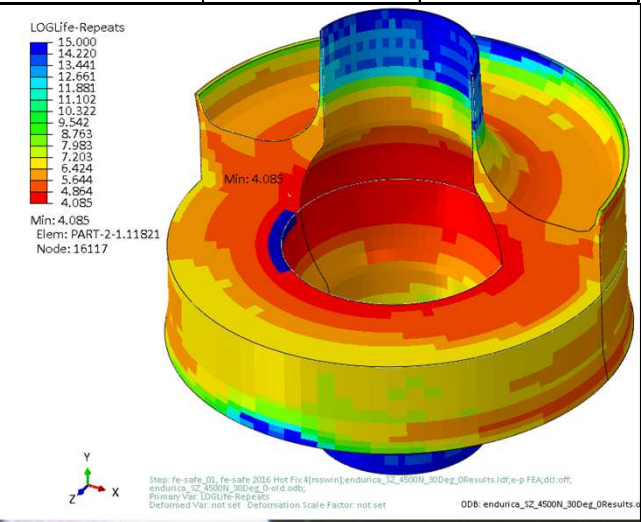
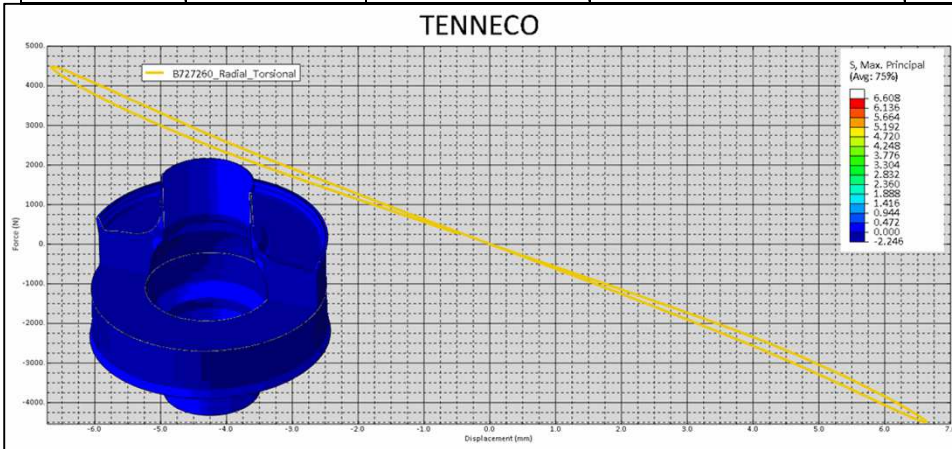
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fe-safe/Rubber – Radial/Torsional Summary



Test Inputs	Test Conditions	Termination Conditions	fe-safe/Rubber Cycles (1 mm Tear)	Cycle of Initial Rate Change	Part Rate Life vs Prediction	Bench Durability Cycles	Tear Length End of Test
Radial & Torsional	+/- 4,500N & +/- 30°	+/-7.75 mm Radial Travel	12,200	13,362	110%	21,374	19.57 mm



Summary of Results



1. Results in the table are from the 5th of 5 life test replicates.
 - As testing progressed, parts were terminated earlier in order to capture the smallest crack possible.
 - fe-safe/Rubber predicts the cycle count to 1 mm of crack growth.
 - The failure location of all the test pieces include the fe-safe/Rubber prediction for the crack location.
 - A 1 mm tear does not produce enough rate change for the durability test equipment to detect.
2. Radial, Axial & Torsional were modeled as half cycles, so table results are ½ of fe-safe/Rubber images on previous slides.
3. Radial/Torsional was modeled as full cycles
4. Actual durability was 10-40% longer than fe-safe/Rubber predictions.

Test Inputs	Radial	Axial	Torsional	Radial & Torsional
Test Conditions	+/- 7,000N	+/- 2,000N	+/- 43°	+/- 4,500N & +/- 30°
Termination Conditions	+/- 9.5 mm	+/-22 mm	80,000 Cycles	+/-7.75 mm Radial Travel
fe-safe/Rubber Cycles (1 mm Tear)	17,257	65,912	37,668	12,162
Cycle of Initial Rate Change	24,132	77,275	50,000	13,362
Part Rate Life vs Prediction	140%	117%	133%	110%
Bench Durability Cycles	28,142	83,685	79,195	21,374
Tear Length End of Test	14.32 mm	17.55 mm	23.57 mm	19.57 mm

Questions