



3DEXPERIENCE®

# **fe-safe/RUBBER™**

ELASTOMER DURABILITY SOFTWARE  
FOR FINITE ELEMENT MODELS



## INDUSTRY CHALLENGES

Developers of rubber materials, components and systems increasingly rely on simulation as a routine means to address design issues.

The demand for simulation of durability is especially strong. Durability often dominates development agendas, and empirical evaluation is by its nature time-consuming and costly. Simulation provides a strategic approach to managing risk and cost by enabling design concepts or design changes to be studied before investment in physical evaluation. For metallic components, solutions for fatigue analysis from FEA have existed commercially for many years and have become an essential part of maturing and qualifying design concepts in many industrial sectors.

## SOLUTION

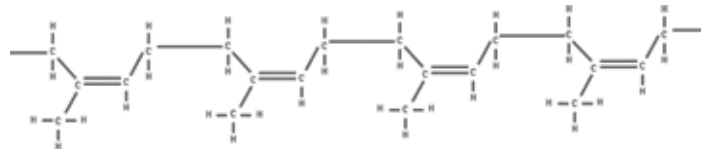
fe-safe®, from the SIMULIA brand of Dassault Systèmes, is the world's leading technology for durability analysis. Its capabilities have been developed to meet the most demanding industry applications. fe-safe is used by leading companies in the automotive, truck, off-highway, marine, military, off-shore, power generation, wind energy, medical engineering and many other industries.

fe-safe was the first commercially available fatigue analysis software to focus on modern multiaxial strain based fatigue methods.

Launched in 2012 fe-safe/Rubber™ is a unique and advanced solution enabling the fatigue analysis of elastomer materials based on technology originally patented by Endurica LLC. fe-safe/Rubber is available as an add-on module to fe-safe.

fe-safe/Rubber is used to analyze the fatigue performance of elastomers under real-world service conditions. Because of their macromolecular structure, elastomers exhibit unique behavior and require specialized analysis methods:

- Finite Strains
- Nonlinear Elasticity
- Strain Crystallization
- Time Dependence
- Temperature Dependence
- Ozone Attack
- Mullins Effect
- Crack closure
- Fatigue Threshold
- Microstructural crack precursor size

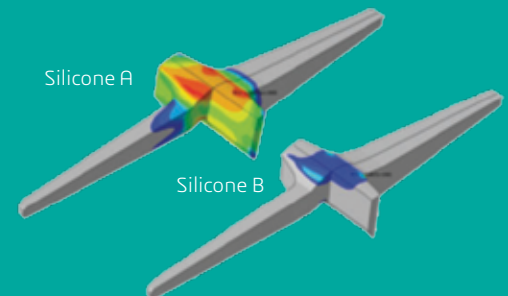
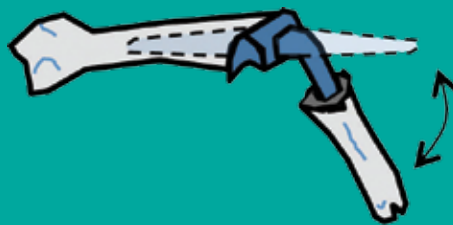


**fe-safe/Rubber is the first commercially available code that specializes in accounting for the factors that govern an elastomer's fatigue life**

## CASE STUDY

### Silicone rubber finger joint prosthesis

This silicone rubber finger joint prosthesis is required to survive 100 million flex cycles. fe-safe/Rubber allows designers to compare the durability of different candidate materials under realistic loading scenarios.



## TECHNOLOGY OVERVIEW

fe-safe/Rubber estimates the fatigue life of a rubber component. Based on the mechanical duty cycle computed with a Finite Element Analysis solution, combined with a specification of the rubber's material properties, it computes the number of duty cycle repetitions that are required to produce a small crack at each location within the component. The duty cycle is read from the finite element model as a time domain signal specifying the components of the strain tensor. After computing the fatigue life for each element, the results from fe-safe/Rubber may be visualized as color contours showing the critical locations where cracks will initiate.

fe-safe/Rubber features a patented critical plane algorithm developed specifically for finite straining. This algorithm accurately accounts for the effects of crack closure and multiaxial loading. It also features a Rainflow counting procedure for identifying and accumulating the damaging effects of each event in the duty cycle. fe-safe/Rubber provides a selection of nonlinear material models that enable accurate representation of the rubber component's behavior, and a database of ready-to-use properties for a number of popular elastomer types.

### KEY BENEFITS

- Increase confidence at the inception of the design cycle
- Save the costs of build and break experiments for well-qualified designs
- Understand your component's failure process from the perspective of its critical features and their localized service experiences
- Use research validated software to make design decisions that accurately account for material behavior and service environment

## Damage Accumulation Law

fe-safe/Rubber computes fatigue life by integrating rubber's fatigue crack growth rate law to determine the number of repeats of the duty cycle that are required to produce a small crack.

## Material Behavior

fe-safe/Rubber provides material modeling features that accurately capture major mechanical, thermal and environmental effects that govern rubber's fatigue behavior. Depending on elastomer type and formulation, the total fatigue crack growth rate may include contributions from both cyclic and steady (static) load inputs, and may reflect the presence (or absence) of strain crystallization. Available models reflect the collected experience of many decades of scientific research into rubber's fatigue behavior and are suitable to represent a very broad range of elastomer types: natural and synthetic, filled and gum, strain-crystallizing and non-strain-crystallizing, thermosets and thermoplastics.

## Critical Plane Analysis

fe-safe/Rubber considers that cracks originate from microscopic features present in the material prior to the application of any loads. These crack precursors are assumed to exist at every point, and in every possible orientation. Each is assumed to grow in a self-similar manner, at a rate that reflects its own individual loading experiences. fe-safe/Rubber computes the fatigue life for each potential failure plane orientation, and identifies the critical plane by minimizing the fatigue life. Critical plane analysis is essential for accurately predicting the effects of loading histories involving compressive loads (where crack closure effects must be considered), and those involving multiple, asynchronous loading components (multiaxial loading).

## Rainflow Counting

After computing the loading history experienced on a potential failure plane, fe-safe/Rubber applies a Rainflow counting algorithm to identify a list of the individual loading event-pairs contained within the original history.

## CASE STUDY

### M1 Abrams tank track backer pad

Qualification testing for the rubber track system in a military vehicle application can cost USD \$2M for a single new design. fe-safe/Rubber enables engineers to study how design and service conditions affect durability, resulting in a more mature candidate for testing.





## PROCESS OVERVIEW

### Specify Materials

Pick from the built-in database or define your own

### Run FEA

Compute strain history(ies)

### Specify Analysis

Set up duty cycle, set temperature, ozone attack options

### Execute

Compute fatigue life, write to model database

### Visualize

Identify and solve durability issues

## VALIDATION CASE

fe-safe/Rubber is based on the Endurica fatigue solver, which embodies over a decade of development work and possesses a formidable validation case.

The Endurica fatigue solver's record includes experimental confirmation that:

- Endurica's patented critical plane algorithm accurately predicts fatigue life and crack orientation for loading histories involving combined tension+shear and compression+shear (Mars and Fatemi 2006a)
- Endurica produces accurate predictions of fatigue life and crack orientation for variable amplitude loading histories, for both uniaxial and multiaxial cases (Harbour et al 2008)
- Endurica correctly predicts the location of crack initiation in an automotive exhaust mount (Mars et al 2005)

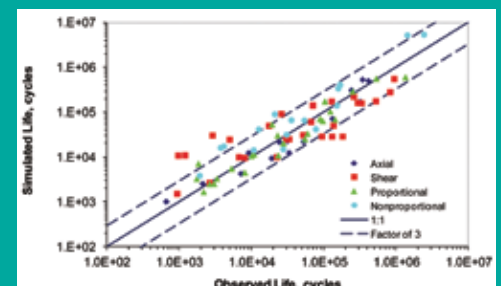
## KEY FEATURES

- Friendly User-Interface from which to access your finite element results, define duty cycles and specify materials
- Accurate Material Models - highly nonlinear stress-strain curves, Mullin's effect, strain crystallization
- Temperature Dependence
- Time Dependence
- Fatigue characterization scheme designed for efficiency and ease of application. fe-safe/Rubber uses material properties that can be directly obtained via readily available experiments
- Pre-populated Materials Database - add proprietary materials to your own database
- Critical Plane analysis for multiaxial loading:
  - a patented critical plane algorithm that considers the individual loading experiences on each potential failure plane of the material
  - considers the effects of finite straining on the motions of each potential failure plane
  - the energy release rate of a hypothetical defect on each plane is estimated as a function of time
  - the possibility of crack closure is considered for each plane at each instance of time
  - the critical plane is identified as the plane that maximizes the rate of damage accumulation
- Rainflow counting on a per-plane basis for variable amplitude loading
- fe-safe/Rubber damage accumulation calculations consider the contribution from each peak and valley

# Navigate your fatigue issues with support from the world leader in rubber fatigue analysis

## CASE STUDY: Multiaxial, Variable Amplitude Experiments

fe-safe/Rubber considers the individual loading experience of each potential plane of crack initiation. Its patented algorithm correctly predicted both life and failure plane orientation for a large set of fatigue tests made under various combinations (both proportional and nonproportional) of tension, compression, and shear, and under variable amplitude loading conditions.



## CAPABILITIES OVERVIEW

### Material Models

- Hyperelastic laws: Neo-Hookean, Mooney-Rivlin, Reduced Polynomial (Yeoh), Arruda-Boyce, VanderWaals, and Ogden
- Softening law (Mullins effect): Ogden-Roxburgh
- Fatigue crack growth rate laws: Thomas, Lake and Lindley, Tabular
- Strain-crystallization laws: Non-crystallizing, Mars and Fatemi, Tabular
- Creep crack growth laws: Power law, Tabular
- Temperature dependence: Exponential
- Ozone attack laws: Williams, Gent and McGrath

### Materials Database

- Natural Rubber (NR), Styrene-Butadiene Rubber (SBR), Butyl (IIR), Polychloroprene (CR), Nitrile (NBR), Polybutadiene (BR), Polyurethane (PUR), Silicone (MQ), others
- Filled and unfilled variations

### Finite Element Model

- Model size limited only by machine resources
- Analysis can be run on a subset of the model, or on the entire model
- Support for both surface (2D) and bulk (3D) strains
- Exact enforcement of plane stress condition for surface elements
- Exact enforcement of hydrostatic pressure for incompressible analyses
- Optional thresholding feature improves run-time for large models by saving critical plane analysis for likely failure sites
- Results from several FE results databases may be combined

### Duty Cycle

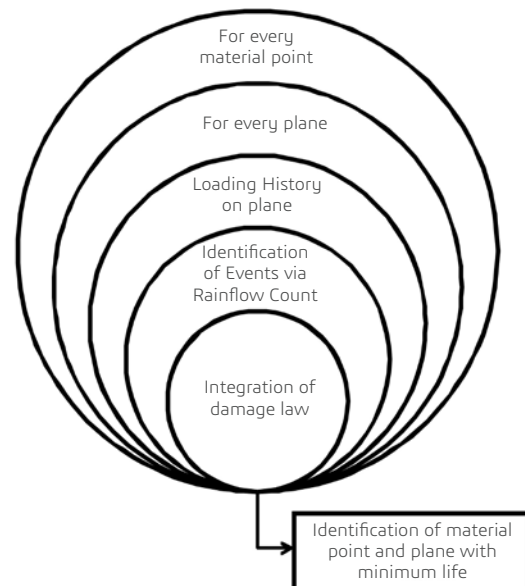
- fe-safe/Rubber operates on time-domain strain history, which is recovered for each node or element to be analyzed
- Complex duty cycles can be constructed from simpler duty cycles by combining FE analysis results
- Mullins effect softening is pre-computed on the basis of the largest strain occurring in the duty cycle

### Analysis

- Critical plane analysis is made on a set of representative planes
- Rainflow counting identifies event-pairs on an individual basis, and preserves indices back into the time-domain signal
- Indices returned from Rainflow counting are useful for finding 'most damaging' events in a complex signal, and for reconstructing abbreviated signals that preserve important events

### Output

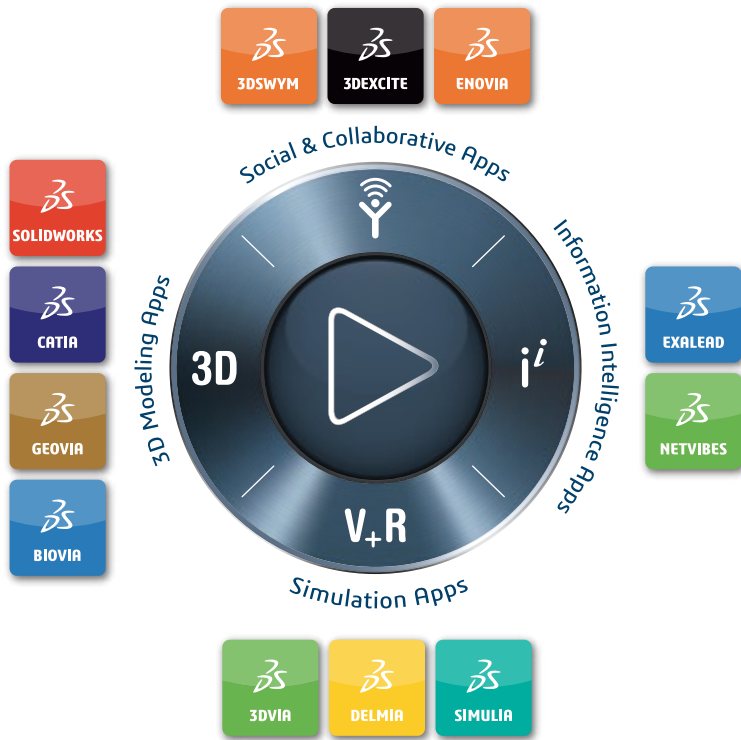
- Fatigue life at each element, in terms of repeats of the given duty cycle
- Contour plot of fatigue life on the rubber component
- Optional outputs
  - Failure plane orientation at each element
  - Local loading experience of the critical plane
  - Dependence of fatigue life on critical plane orientation
- Rainflow count of the local loading experience of the critical plane, including indices back to the original time-domain signal



*This is not a complete list of features in fe-safe/Rubber.*

### References

- W. V. Mars, A. Fatemi, 2006a, Nucleation and Growth of Small Fatigue Cracks in Filled Natural Rubber Under Multiaxial Loading, *Journal of Materials Science*, Vol. 41, pp. 7324-7332.
- W. V. Mars, A. Fatemi, 2006b, Analysis of Fatigue Life Under Complex Loading: Revisiting Cadwell, Merrill, Sloman, and Yost, *Rubber Chemistry and Technology*, Vol. 79, No 4, pp. 589-601.
- W. V. Mars, J. Kingston, A. Muhr, S. Martin, K. W. Wong, 2005, Fatigue Life Analysis of an Exhaust Mount, *Constitutive Models for Rubber IV*, Austrell, Kari (eds.), Swets and Zeitlinger, Netherlands, pp. 23-30.
- R. Harbour, A. Fatemi, and W. V. Mars, 2008, Fatigue crack orientation in NR and SBR under variable amplitude and multiaxial loading conditions, *Journal of Material Science*, 43, 1783-1794, 2008.
- W. V. Mars, A. Fatemi, 2003, A Phenomenological Model for the Effect of R ratio on Fatigue in Strain Crystallising Rubbers, *Rubber Chemistry and Technology*, Vol. 76, No 5, pp. 1241-1258.
- W. V. Mars, 2009, Computed Dependence of Rubber's Fatigue Behavior on Strain Crystallization. *Rubber Chemistry and Technology*, Vol. 82, No. 1, pp. 51-61.
- W. V. Mars, 2001, *Multiaxial Fatigue of Rubber*, PhD dissertation, University of Toledo.



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