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Accelerating Reliable Design

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Using ENDURICA to Compare Two Rubbers Under Multiaxial Spectrum Loading

Overview

In this example, two rubbers of identical stress-strain behavior, but differing fatigue and strain-crystallization properties (filled NR and filled SBR), are compared for their ability to endure a specified loading history.

Duty Cycle

The loading history considered in this example is defined in terms of the 3 strain tensor components shown in Figure 1. The history of the other 3 strain tensor components is computed by the ENDURICA code, according to the assumption that the loading is plane stress, and that the material is nearly incompressible. The loading history for each channel contains a range of frequencies, and each is shown in Figure 2.

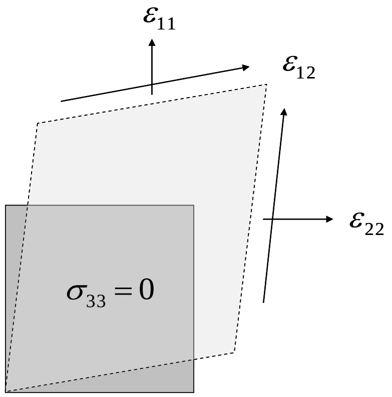

Figure 1. Strain history is defined in this example using 2 axial components, and 1 shear component. The plane stress condition is enforced.

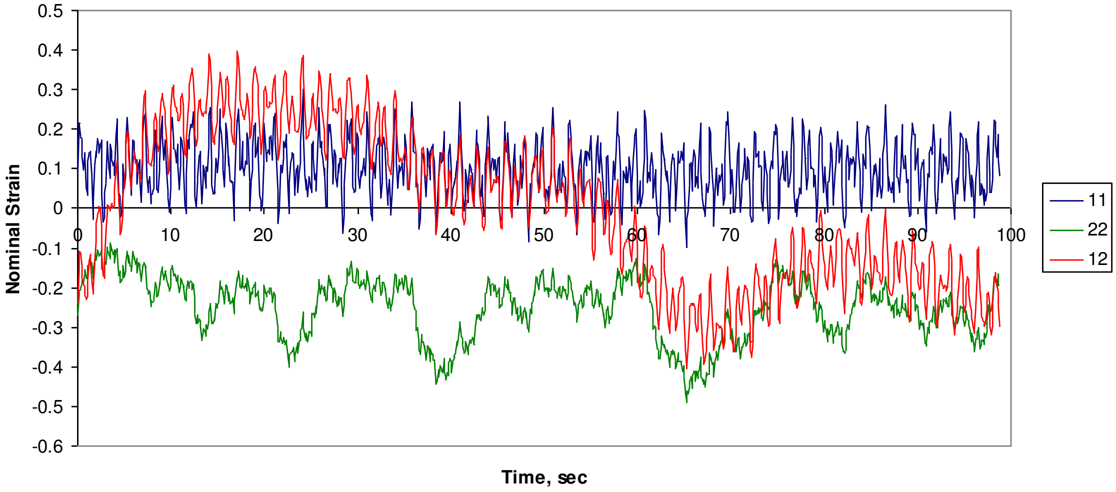

Figure 2. History of strain tensor components used for this analysis.

Materials

In this example, two filled elastomeric materials are considered: Natural Rubber (NR) and Styrene Butadience Rubber (SBR). NR is an example of a strain crystallizing rubber. SBR is an example of a non-strain crystallizing rubber.

Through the selection of compound ingredients and curing conditions, stiffness and fatigue properties typically can be varied somewhat independently, and a wide range of properties is possible. For purposes of this study, it is assumed that the stress-strain behavior of the two rubber compounds is identical, and that the compounds only differ in their fatigue properties. Table 1 presents the material definitions that are used for the analysis.

Table 1. Material parameters defining stress-strain and fatigue behavior.

! Filled SBR MAT=FILLEDSBR ELASTICITY_TYPE=NH+MULLINS SHEAR_MODULUS=3e6 Pa BULK_MODULUS=3000e6 Pa MULLINSR=1.65 MULLINSM=2.0e6 Pa MULLINSBETA=0.1 FATIGUE_TYPE=LAKELINDLEY FLAWSIZE=100E-6 M FLAWCRIT=1E-3 M RC=7E-6 (M/CYCLE) TCRITICAL=10000 J/m^2 THRESHOLD=60 J/m^2 TRANSITION=400 J/m^2 F0=4	! Filled Natural Rubber MAT=FILLEDNR ELASTICITY_TYPE=NH+MULLINS SHEAR_MODULUS=3e6 Pa BULK_MODULUS=3000e6 Pa MULLINSR=2.25 MULLINSM=1.0e6 Pa MULLINSBETA=0.1 FATIGUE_TYPE=LAKELINDLEY FLAWSIZE=100E-6 M FLAWCRIT=1E-3 M RC=1E-6 (M/CYCLE) TCRITICAL=10000 J/m^2 THRESHOLD=40 J/m^2 TRANSITION=450 J/m^2 F0=2 X(R)=LIST

The stress-strain behavior implied by the parameters selected is shown in Figure 3. Filled rubber exhibits a pronounced softening of its stress-strain behavior, depending on the extent to which the material is cyclically pre-loaded (the Mullins effect). Typical curves are shown here at 3 different levels of pre-loading, and 3 different modes of deformation.

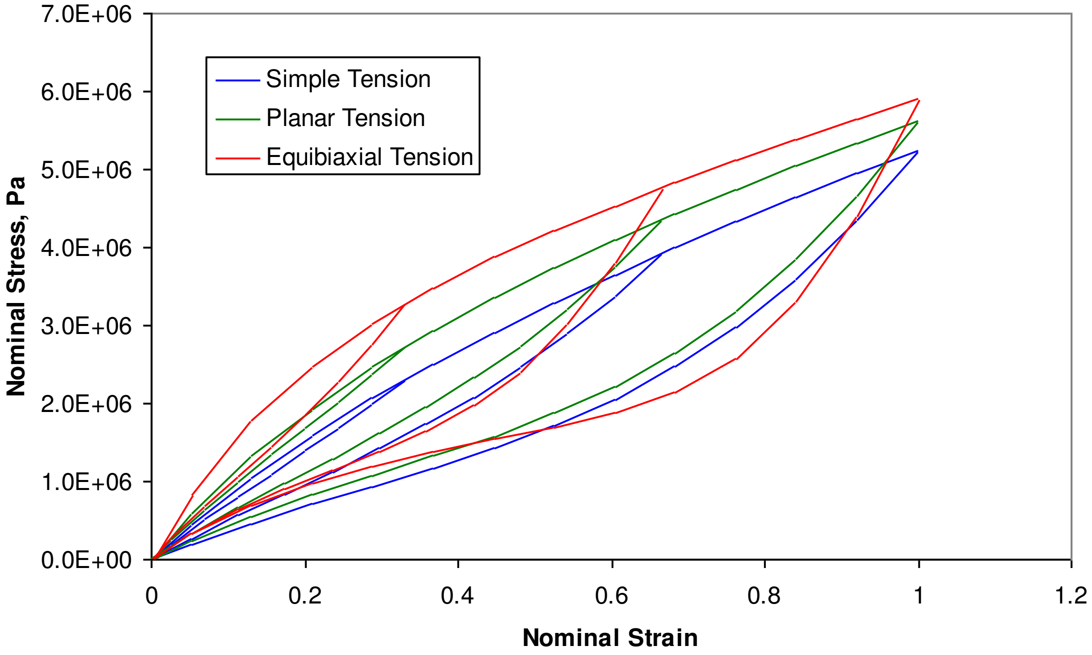

Figure 3. Cyclic stress-strain behavior of rubber, including the Mullins effect, in deformation states of simple tension, planar tension, and equibiaxial tension.

The fatigue crack growth behavior of rubber depends strongly on strain-crystallization. Figure 4 compares the behavior of the two compounds under conditions in which the loading cycle is fully relieved between cycles (also known sometimes as $R = 0$ loading). Filled NR is the strongest material, and its crack growth rate has a lower sensitivity to changes in loading than SBR. On the other hand, SBR has a higher mechanical threshold than NR. This means that the question of which material is the most durable depends on the duty cycle. If the duty cycle remains below SBR's threshold, but above NR's, SBR will be the most durable. If the duty cycle includes many events above SBR's threshold, then NR will be the most durable.

Strain crystallization has a profound effect on the sensitivity of crack growth to R ratio. Figure 5 compares crack growth curves in cases where the loading does not fully relax between cycles. In the case of SBR, R ratio is seen to have the modest effect of shifting the crack growth curve, so that as R ratio increases the crack growth rate drops off slightly. In the case NR, R ratio has a dramatic effect. The slope of the crack growth curve depends strongly on the R ratio, and a drop in R ratio of only 10% can retard crack growth by a factor of more than a factor of 10.

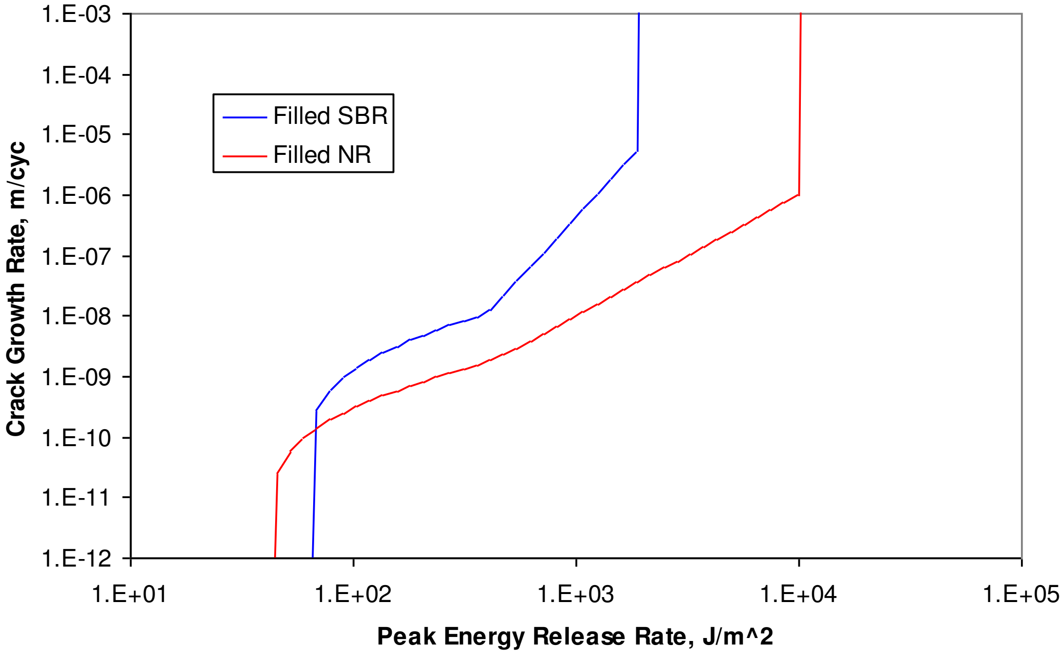

Figure 4. Fully relaxing crack growth behavior of filled NR and SBR compounds. NR is stronger than SBR, but SBR has a higher fatigue threshold than NR.

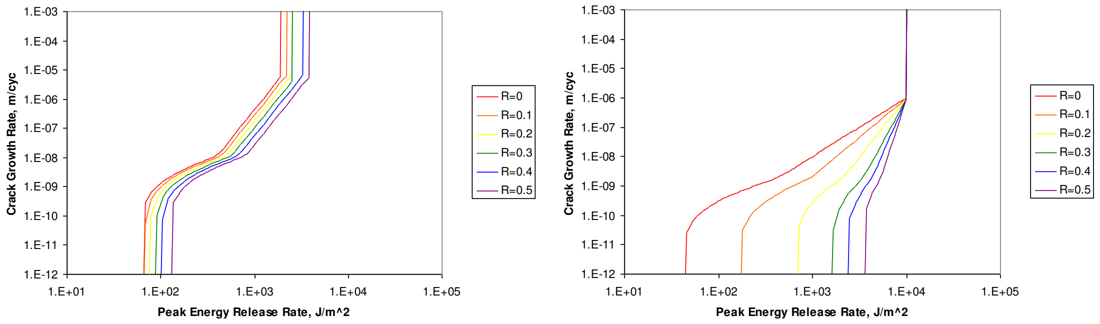

Figure 5. Fatigue crack growth curves, reflecting the effects of strain crystallization. Strain crystallizing materials are very sensitive to R ratio.

The fatigue crack nucleation behavior is often of interest. Given the curves in figures 4 and 5, the fatigue crack nucleation life can be computed and presented in the form of a Haigh diagram. The Haigh diagram shows the effect of strain amplitude and mean strain on the fatigue life, see Figure 6. Strain crystallization in NR gives rise to the increase in fatigue life that is shown when the tensile mean strain is greater than the strain amplitude.

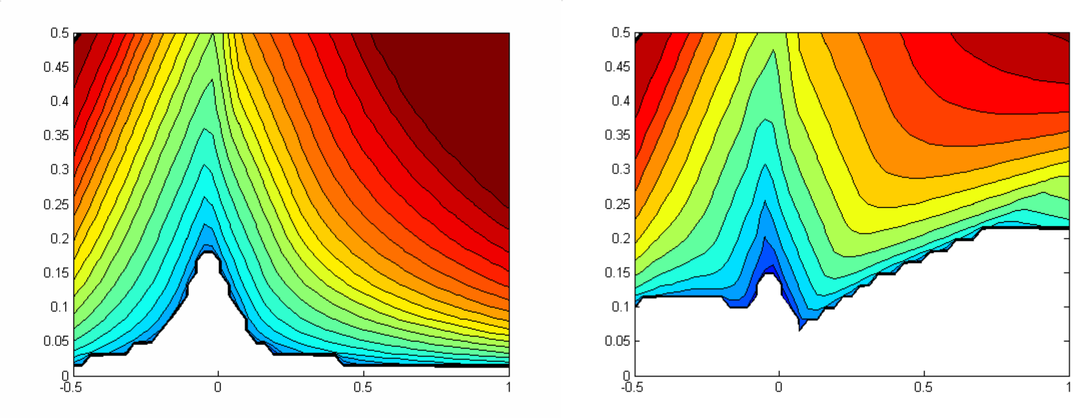

Figure 6. Computed Haigh diagrams for filled SBR (left) and filled NR (right) under simple tension / compression. X-axis = Mean Strain, Y-axis = Strain Amplitude, contours colored according to fatigue life (red = shorter, blue = longer).

Failure Site Experience

The principal stresses corresponding to the applied strain history are shown in Figure 7. The tensor-valued stress and strain histories are used to compute, for each potential plane of failure, the local history of loading on the plane. The local history is then parsed via the Rainflow procedure, and used to compute the fatigue life of each potential failure plane. The failure plane is finally identified as the plane with the shortest fatigue life.

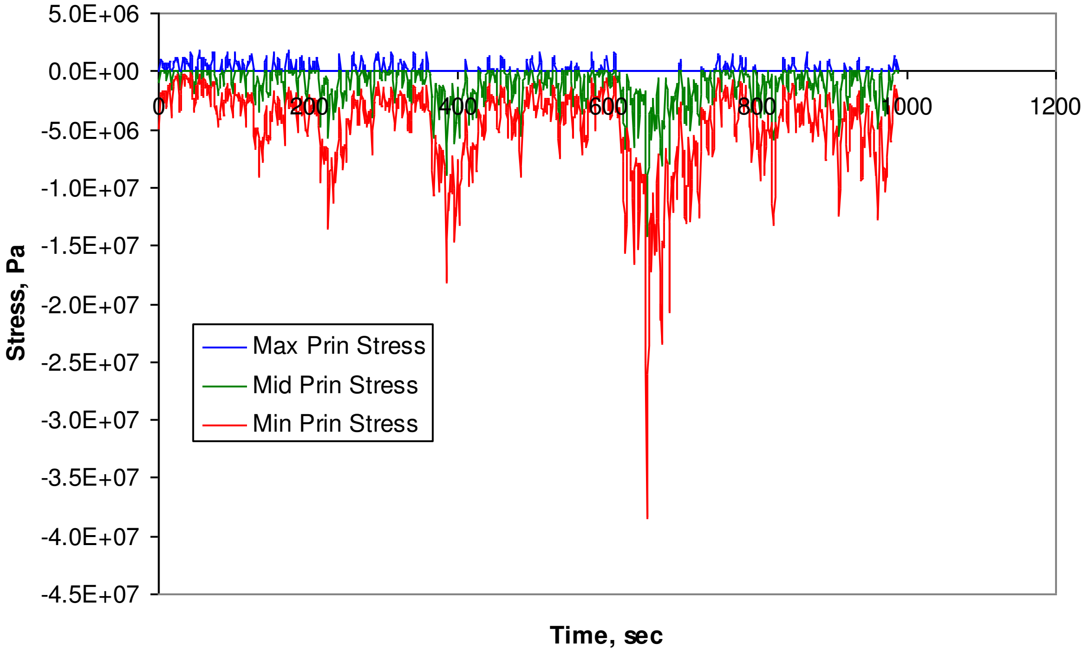

Figure 7. History of principal stresses.

The Rainflow count of the history generally depends on the plane evaluated, as shown in Figure 8. Figure 9 shows the range and mean identified from the local history on the failure plane, which happens for these two materials to be identical. This information can be used to identify events in the history which are unusually severe.

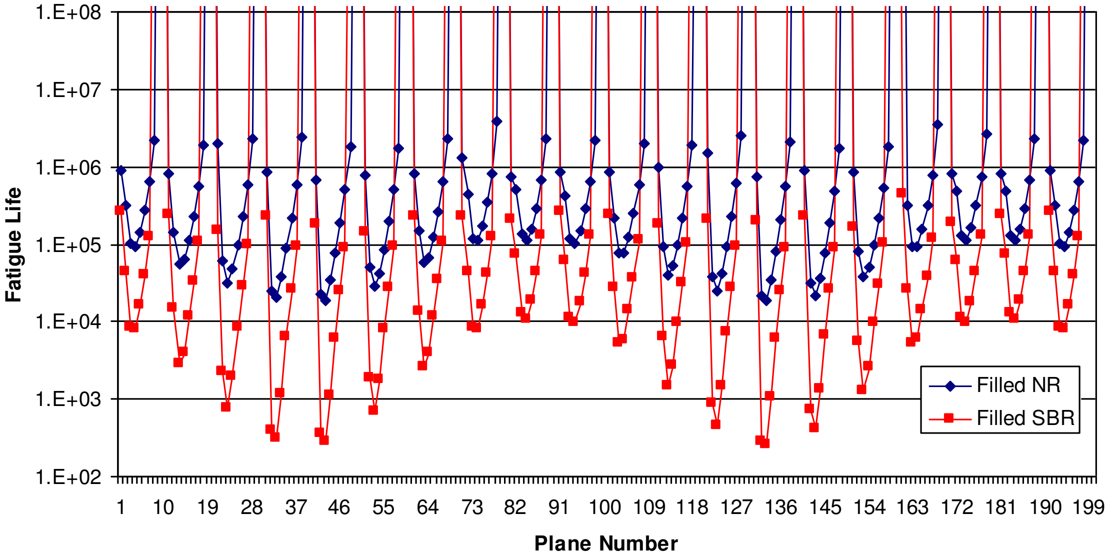

Figure 8. Dependence of fatigue life on plane. For this analysis, 200 planes were evaluated.

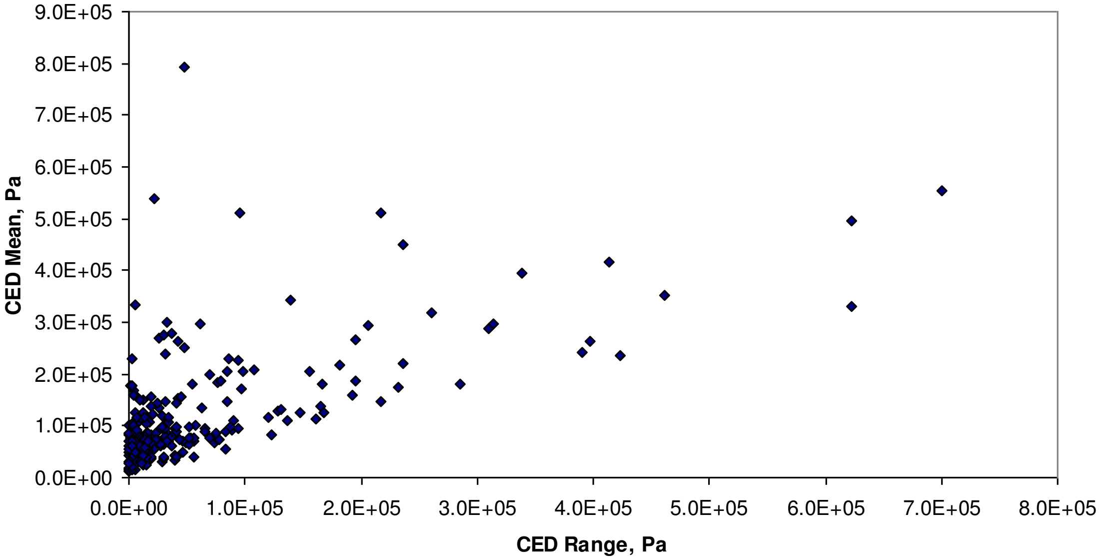

Figure 9. Range and Mean of individual cycles on the failure plane as identified via the Rainflow counting procedure.

The failure plane prediction can be presented as a contour plot on the unit sphere representing all possible failure planes (the plane unit normal vector is a point on this sphere), as shown in Figure 10. Here, contours are colored according to the fatigue life of the failure plane. In developing accelerated versions of the duty cycle for product development, it would generally be desired to maintain a similar distribution.

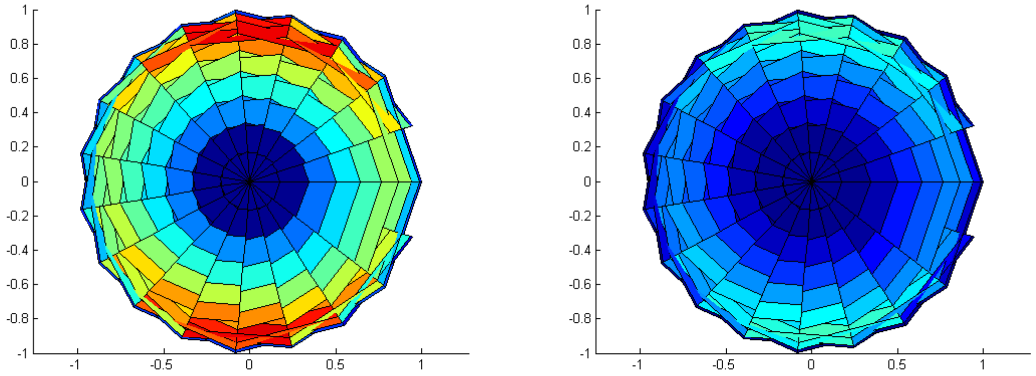

Figure 10. Distribution of damage among potential failure planes, Filled SBR (left), Filled NR (right). Contours in both images are colored on the same scale, according to predicted fatigue life. Red is short life (100 repeats), blue is long life (1x10^6 repeats).

Conclusion

For the duty cycle given in Figure 2, the Filled NR compound endures better than the Filled SBR compound. As shown in Figure 11, the difference amounts approximately to a factor of 70.

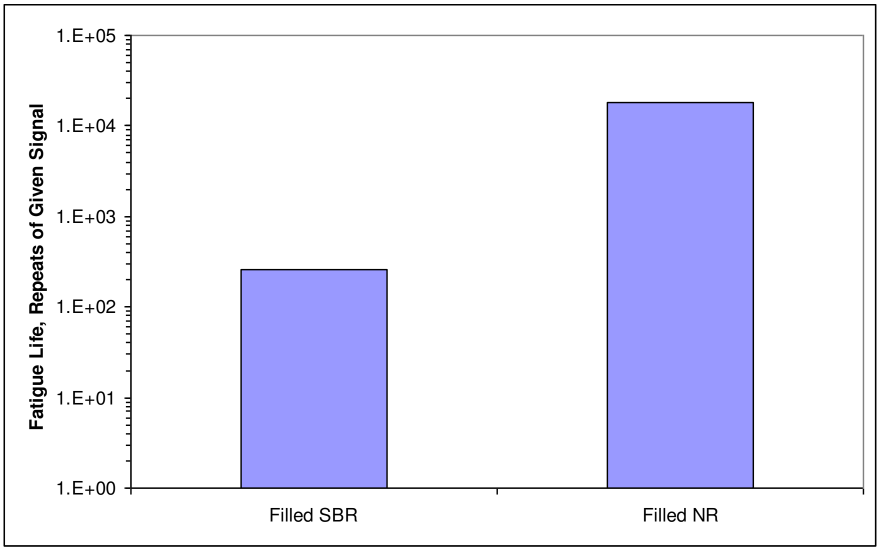

Figure 11. Filled NR is 70 times more durable than Filled SBR for the duty cycle considered.