FATIGUE LIFE PREDICTION OF NATURAL RUBBER COMPONENTS FOR UNIAXIAL AND MULTIAXIAL LOADINGS

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In this paper, the fatigue lifetime of natural rubber (NR) components is investigated, and a criterion predicting the number of cycles to initiation (N_i) of a short crack is proposed. Uniaxial test results require a diagram which plot the stress amplitude versus the mean stress.

A first extension to cyclic multiaxial tests was carried out using two kinds of axisymmetrical notched samples (AE5 and AE2 specimens) tested under repeated uniaxial and torsion loadings. The corresponding 2D and 3D simulations with finite element analyses (F.E.M.) give the Cauchy stress fields. The results suggest that the largest principal stress versus mean hydrostatic pressure diagram is well suited for the prediction of the cycles to initiation (N_i) in many NR components.

INTRODUCTION

Natural rubber (NR) shows good performances in fatigue. Many studies dealing with fatigue crack propagation are published (e.g. (1)), but we can find less fatigue results with smooth samples (2) and few in the range of fatigue crack initiation (3).

At first, this work presents tension-compression and tension-tension cyclic tests carried out on axisymmetrical uniaxial-like samples. For each test, the values of the axial local Cauchy stresses in the initiation zone are deduced from finite element computations. The stabilized mechanical behaviour of the rubber studied here is modelled using a classical form of the generalised Rivlin law with five parameters (4). In tension-compression, the axial stress range seems to be the main parameter. For tension-tension loadings the axial mean stress has a greater influence. Therefore, the Haigh diagram (i.e. Stress range versus mean stress) is then built up for plotting the endurance test results. The fatigue iso-lifetime curves are drawn on this Haigh diagram. They can be used as fatigue life criterion which predicts the initiation of a short crack.

Secondly, two axisymmetrical notched samples (AE5 and AE2) were tested under tension-compression, tension-tension and torsion conditions. The AE samples tested in torsion clearly show that the largest principal stress determines the orientation of the initial cracks. In addition, the experimental fatigue data reveal a limited dependence with respect to the triaxiality ratio. On the basis of such results, we suggest that a diagram plotting the largest principal stress range against the mean hydrostatic pressure is well suited for predicting the cycles to initiation (N_i) . The multiaxial tests results are presented in this new diagram, using the Cauchy stresses calculated beneath the notch root (initiation zone). The last part of the paper is devoted to the comparison with the predictions based

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on uniaxial fatigue iso-lifetime curves plotted in such diagram which give conservative results.

EXPERIMENTAL AND NUMERICAL PROCEDURES

Uniaxial and multiaxial fatigue tests were carried out at room temperature, using a sinusoidal low frequency signal (~1Hz), under displacement control, respectively on a set of diabolo shape uniaxial-like samples (tension-compression and tension-tension tests) and on two set of axisymmetrical notched specimens AE5 and AE2 with notch radius of ~5mm and ~2mm (tension-compression, tension-tension and torsion tests). The experimental fatigue results and the detailed data dealing with the specimen geometries, with the investigated carbon black filled Natural Rubber NR and his classical non-linear elastic behaviour are presented elsewhere (5).

In our tests under constant strain amplitude, the stress amplitude decreases during some 100 cycles to an extent of about 10%. After this stage, the stress amplitude remains constant up to ~90% of the time to rupture of the samples. Then, for plotting the endurance test results, stabilized stress distributions were computed (Finite Element Method FEM) using the ZeBuLon code at Ecole des Mines de Paris (6). Axisymmetrical 2D simulations were performed for tension and compression loadings whereas torsion tests required 3D calculations. On all the notched specimens the local stresses remain more severe in the notch root.

A long time before the final rupture, short fatigue cracks initiate on the lateral surface of the samples (see for example in figure1-a the notch root of an AE2 specimen tested in torsion). In figure 1-b, a scanning electronic microscope (SEM) observation of a uniaxial fatigue specimen indicate that the initiation depends on small defects (here a carbon black agglomerate) with a diameter of about 100 μm. The numbers of cycles to initiation are difficult to be determined unambiguously. It is yet unclear whether short cracks start growing slowly as soon as the load is applied or whether no crack growth takes place during an incubation period. Therefore, a conventional definition of the cycles to initiation is proposed : N_i is the number of cycles necessary for a surfacic pre-existing microscopic defect to grow up to a ~1mm size detected by optical observations.

RESULTS AND DISCUSSION

For crystallising elastomers such as the present Natural Rubber, it appears that the effect of crystallisation increases the differences in fatigue behaviour between tension-compression and tension-tension tests. Thus, the stress range is not sufficient to predict the fatigue life. of NR components. In fact, as classically known in fatigue, two variables are needed to estimate the lifetime.

Uniaxial Results

As shown in Figure 2, the Haigh diagram allows us to use two mechanical parameters, stress amplitude $S_a=(S_{max}-S_{min})/2$ versus mean stress $S_m=(S_{max}+S_{min})/2$. Moreover, it gives a good overview of both loading ratio effects when R>0 and R<0 with $R=S_{min}/S_{max}$. A solid straight line is plotted for ratio R=0, which clearly separates both set of data.

For each uniaxial-like diabolo test, the stresses S_m and S_a are calculated as previously explained and (Figure 2). Moreover, in each point an index indicates the corresponding cycles to initiation N_i (10^5 cycles).

For tests with large compressive stresses ($S_m<0$ and $S_a<1$ MPa) or high stress ratios ($R>0.2$), it can be seen that the material remains undamaged. Figure 2 shows that fatigue life always decreases as the stress amplitude increases. For $R<0$, the mean stress S_m produce a classical effect; the fatigue life decreases, as S_m increases. On the other hand there is a beneficial effect of S_m for loading ratio with $R>0$. For example, around $S_a\approx1$MPa and $S_m\approx1.3$MPa, a change of 20% on S_m will extend the fatigue life from $N_i=0.7\times10^5$ to $N_i=6.5\times10^5$ cycles.

In figure 3, on the basis of the uniaxial fatigue tests, we have fitted four iso-lifetime curves using four couples of dashed parallel straight lines corresponding to $N_i=10^5$, $N_i=2\times10^5$, $N_i=3\times10^5$ and $N_i=5\times10^5$ cycles. These so-called iso-lifetime curves are calculated as follow :

$$\begin{array}{lll} \text{for } R<0: & S_{eq}=S_a+a_1 .S_m & \\ \text{for } R>0: & S_{eq}=S_a+a_2 .S_m & \quad [1] \\ \text{where} & a_1=3.12 \quad \text{and} \quad a_2=-7.61 & \end{array}$$

The fatigue equivalent stress S_{eq} is correlated to the cycles to initiation N_i using a power law equation

$$N_i=\{ S_{eq}/S_0 \}^n \qquad [2]$$

with N_i(10^5 cycles) $S_0=3.52$MPa and $n = -1.99$

A given uniaxial fatigue test will be plotted in this diagram knowing both loading parameters S_m and S_a. So, in comparison with the iso-lifetime curves the cycles to initiation N_i must be estimated.

Multiaxial Test Results

Predictions of fatigue life for structural components require an extension of the present database to multiaxial loadings. A first extent was performed on two kind of axisymmetrical notched samples, with notch radii of about 5mm (AE5) and 2mm (AE2), tested in tension-compression or in tension-tension. The loading is characterised by the extremum of the axial Cauchy stress values calculated in the notch root. The AE5 test results exhibit tiny differences with regard to uniaxial results. With AE2 samples, the comparison shows that for a given axial (local) loading, the number of cycles to initiation are slightly larger than the diabolo ones. We will say that the predictions based on the uniaxial criterion are conservative. Such experimental data seems to attest a more limited dependence with respect to the triaxiality ratio. These results can be found in reference (6).

A fatigue program based on AE2 notched samples tested in torsion under strain control conditions can confirm some of the previous results. Figure 1-a shows the notch root of an AE2 sample observed just after the initiation of short cracks (here $N_i=1.1\times10^5$). For this test, the torsion loading is of a range of angular rotation θ : $[\theta_{min}, \theta_{max}]=[0°, 80°]$.

The orientation of the damaged facets measured with respect to the axis of the sample at $\theta=0°$ (undeformed state) is ~50°. The directions of the largest principal stress calculated in the notch root for both minimum and maximum values of the rotation ($\theta\approx0°$ and $\theta=80°$) are respectively 47° and 61° (with respect to the axis of the AE2 specimen), i.e. approximately perpendicular to the short cracks. These results suggest that the largest principal stress may be the main local parameter dealing with the multiaxial fatigue damage mechanisms.

Although a fully investigation is out of the scope of the present paper to justify our choice, we suggest that a diagram plotting the largest principal stress range against the mean hydrostatic pressure is well suited for predicting the cycles to initiation (N_i). Using the Cauchy stresses, previous results were reported in Reference (6). N. André has shown that such parameters were more relevant. This part is still ongoing with the Ph.D. work of N. Saintier in order to propose a post-processing which gives the map of the fatigue lifetime for both NR test specimens and automotive structural bearings.

CONCLUSION

1. For each cyclic uniaxial-like test, the stresses are plotted in a Haigh diagram using the extreme values of the axial Cauchy stresses simulated by FEM for all the samples on the basis of a non-linear elastic analysis.

2. Two main regimes take place in fatigue life depending on the loading ratio R. A classical scheme is found for R<0 tests, where the life to initiation N_i is a decreasing function of both stress amplitude and mean stress. For R>0, the mean stress has a large influence, improving the fatigue life. Iso-lifetime curves N_i=constant were drawn in the Haigh diagram and should be used for uniaxial fatigue life predictions.

3. The number of cycles to initiation of notched samples (AE) tested under tension-compression conditions can be compared with the uniaxial fatigue iso-lifetime curves. The predictions based on the extremum of the axial Cauchy stress values calculated in the notch root are conservative.

4. A fatigue program based on AE2 notched samples tested in torsion suggests that the largest principal stress is the main local parameter dealing with the multiaxial fatigue damage mechanisms.

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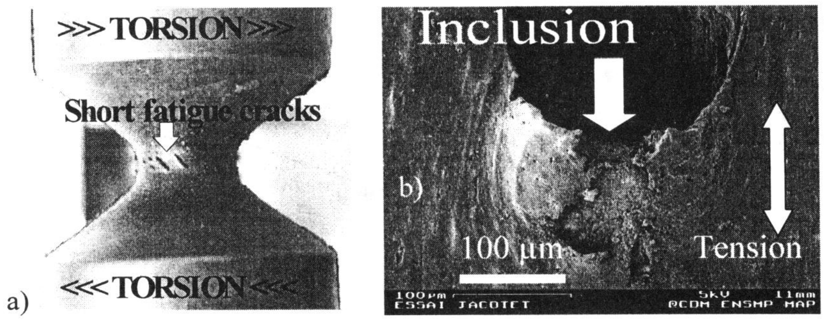

a) AE2 specimen tested in torsion

b) SEM observation of a carbon black agglomerate (∅ ~ 100 μm).

Figure 1 : Short fatigue cracks at initiation.

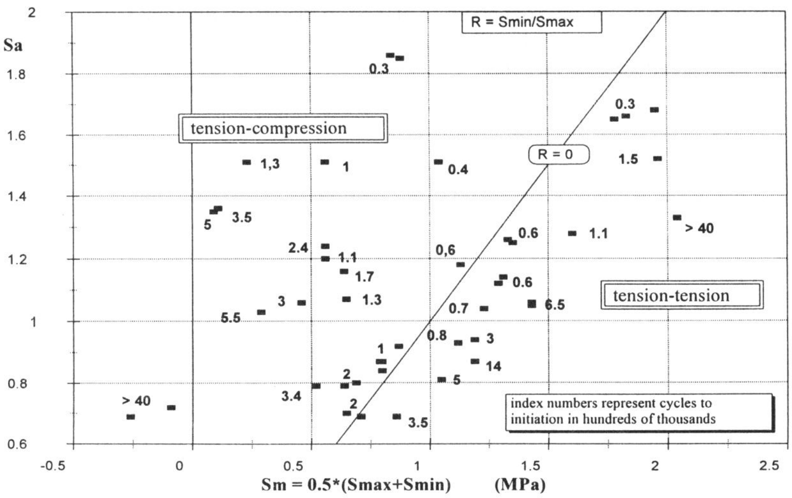

Figure 2 Haigh diagram . Fatigue test loading conditions for uniaxial-like NR specimens

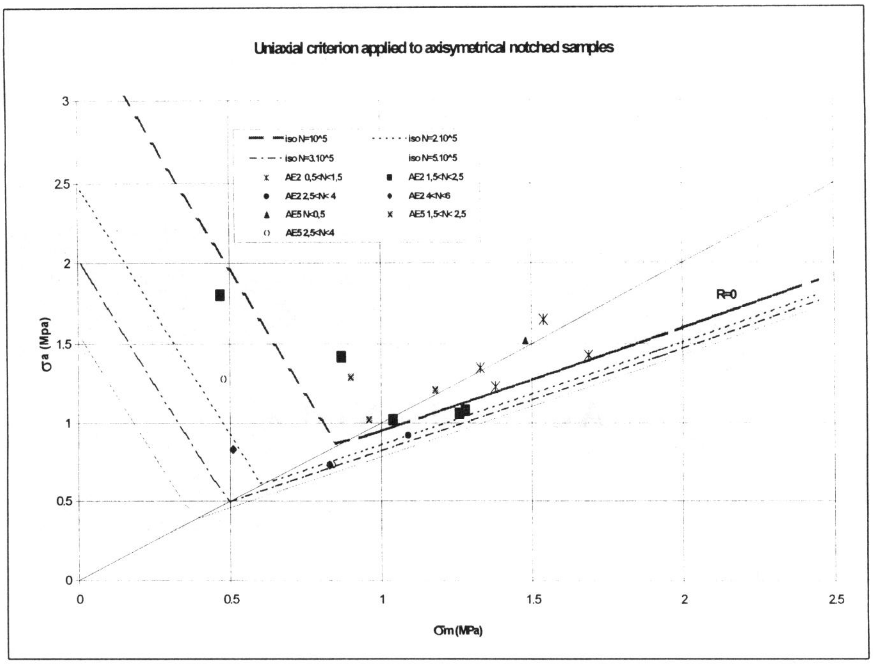

Figure 3 : Fatigue life uniaxial criterion plotted in the Haigh diagram (stress amplitude σ_a versus mean stress σ_m), identified on uniaxial-like NR specimens and applied to NR axisymmetrical notched samples.