EXPERIMENTAL APPROACH OF DAMAGE CUMULATION IN HIGH CYCLE FATIGUE WITH RANDOM LOADINGS IN BLOCKS

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To approach damage cumulation in high cycle fatigue under variable amplitude loadings we have carried out tests on 100 smooth specimens in spheroidal graphite cast iron under random loadings in blocks. For each spectrum loading, block duration is short compared to the number of cycles to failure. The stress amplitude is constant in each block, five different values with the same probability of appearance are possible. We have verified that the total life is a log-normal variable. The loading history has no influence on the lifetime in mean in Plane Bending and in Torsion. The interpretation of all test results has been done by taking into account the scatter of experiments. Stress levels equal to the endurance limit are acting on the failure process. The previsions of the tested cumulative damage rules are not in good agreement with experiments.

INTRODUCTION

Since the Miner's rule (1) many cumulative damage rules have been proposed. Usually, they have been formulated from test results on specimens under loadings with only two blocks. But such loadings are very different from reality. In order to evaluate the behaviour of a spheroidal graphite cast iron under loadings closer to real loadings than those with two blocks we have carried out tests under variable amplitude loadings varying in many blocks randomly arranged.

EXPERIMENTATION

Material.

The material is a spheroidal graphite cast iron. Its designation is close to FGS 800-2 (AFNOR standard). Its main static characteristics are given in (2). The characteristics of this cast iron in high cycle fatigue and fully reversed solicitations are shown in Figure 1. Each S-N curves were determined with 50 specimens (2).

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The model of S-N curve proposed by Bastenaire (3) and the ESOPE software (4) were used to analyse all these test results.

Specimens and loading spectrums.

All experiments were carried out on cylindrical specimens with a median torus involving a theoretical stress concentration factor Kt equal to 1.07 in plane bending. The roughness of the median torus is such that Ra ≤ 0.20 µm.

We have chosen to impose loading spectrums varying in blocks with 5 different amplitudes and the same appearance frequency for each amplitude. For each loading spectrum the apparition order of blocks is random. Three loading spectrums were tested in four points Plane Bending and three others in Torsion. These solicitations were fully reversed. The stress amplitudes in Torsion, τ_i, were chosen with an equi-repartition in stress from the S-N curve of the material under constant amplitude between 10^5 cycles and infinite life (Figure 1). For the loading spectrums in Plane Bending, each stress amplitude σ_i was chosen such that the life on the S-N curve would be almost equal to the life in torsion under the corresponding τ_i stress level as shown in Figure 1.

All the blocks are with constant duration equal to 5000 cycles. This duration is short enough to have a great number of blocks applied on the specimen when failure occurs. But not too short compared with the duration of a transition between two blocks on the testing machine (5). This duration is needed by the testing equipment for passing from the lowest to the highest stress level, it is less than 10 cycles at the operating frequency of 50 Hz. The apparition order of each block was chosen at random by drawing of lots without putting back. Three loading histories were determined like this, an example is shown in Figure 2. To be sure that the real loading history supported by each tested specimen would be representative of a loading spectrum with equi-probable blocks, we verified after each test that the difference between the experimental apparition frequency of each stress amplitude and the theoretical apparition frequency (the same for each stress level) is not significant with a confidence level of 0.95 (6).

Experimental results.

Statistical Analysis method of test results. Under constant amplitude loadings the distribution of the experimental numbers of cycles to failure, *N*, is well-known by the work of Bastenaire (2), but the literature is poor on this subject for variable amplitude loadings. The cumulated frequencies method was applied to analyse our results. We had to verify that the distribution of *N* is log-normal. Two statistical hypothesis tests were applied on all our test results : Kolmogorov-Smirnov (7) and Shapiro-Wilk (8) with a confidence level of 0.95. According to these tests the log-normal hypothesis can be accepted for *N*. The cumulated frequencies method is valid for our tests.

Results. Test results are shown in Figure 3. With the testing machine used (5), a test is stopped when a macro crack of about 0.5 to 1 mm in depth exists in the specimen.

DISCUSSION

Loading spectrums.

As shown in Figure 3, all test results under spectrum loadings seems to be around the same median value. To take into account the scatter of experiments in this remark we have used an hypothesis test proposed by Schwob and Perache (7). In this test two experimental mean values are compared to know if their difference is significant or only due to chance. This test was applied on all results under spectrum loadings. With a confidence level of 0.95 the following conclusions can be derived :
- for each type of fully reversed solicitation, Torsion or Plane Bending, lifetimes are not significantly different in mean for the three loading spectrums tested,
- for each loading spectrum (1, 2, 3), lifetimes are not significantly different in mean whatever the solicitation is.

We can conclude that if there is a large number of blocks with different amplitudes and an equi-probability of appearance, the apparition order of each block has no influence on the lifetime of the material in mean. This result is in contradiction with two blocks experiments, as well as the predictions of many cumulative damage rules. An effect of average seems to exist when there are many blocks.

Many cumulative damage rules have been reviewed from the literature : Miner (1), Henry (9), Corten and Dolan (10), Manson and al (11), The Unified Theory (12), Lemaitre and Chaboche (13), Subramanyan (14), Papadopoulos (15). Excepted the Lemaitre and Chaboche rule, all the others have been formulated and are available for loadings above the endurance limit. Nevertheless, the first four one have been compared with experiments because their formulation is defined when N_i tends to infinity. The Lemaitre and Chaboche rule is not presented herein because, with the constants identified from our test results, its predictions are very far from experiments.

For each case of loading and each rule, the Relative Error of Prevision, *REP*, defined by expression (1), is calculated in Table 1. If the *REP* is negative the rule is non conservative, e.g. its use is dangerous in a design department.

$$REP(\%) = \left((Nmed)_{\exp} - N_{theo}\right) \times 100 \Big/ \left((Nmed)_{\exp}\right) \qquad (1)$$

$(Nmed)_{exp}$: median value of N from experiments $\quad N_{theo}$: prediction of the rule

Table 1 shows that all rules are generally non conservative for the tested loading spectrums. Previsions are not in good agreement with experiments excepted in Torsion under the spectrum number 2. A possible cause of these differences is that these rules do not take into account the influence of the blocks which have a stress level equal to the endurance limit of the virgin material. In the six test configurations the lowest stress levels are equal to the endurance limit (Figure 1).

TABLE 1 - *REP (%)* for each rule and each loading spectrum.

Solicitation	TORSION			PLANE BENDING		
Spectrum number	1	2	3	1	2	3
Miner	-22.7	-6.9	-25.3	-37.6	-20.2	-32.2
Henry	-16.0	3.3	-5.9	-34.1	-11.3	-16.8
Corten. Dolan	-12.8	1.9	-6.9	-36.2	-20.1	-30.0
Manson	-16.5	-2.2	-22.3	-30.7	-15.2	-29.0

Other tests.

To determine qualitatively the effect of such blocks on the lifetime, we have carried out two test series under loadings with two different stress amplitudes. The low stress level is the endurance limit of the solicitation (e.g. stress level number 1 in Figure 1), the high stress level is the third one in Figure 1. Each amplitude was applied alternatively on specimens by blocks of 5000 cycles until failure. These test results are shown in Figure 3. The hypothesis of a log-normal distribution for N has been validated with a confidence level of 0.95 for these two test series.

The comparison of the two experimental mean values led us to conclude (with a confidence level of 0.95) that lifetimes are different in Plane Bending and in Torsion. This is different from the results under loading spectrums. Furthermore, we can notice that the experimental median values of N are very different from the theoretical value, N^*, corresponding to non influence of the blocks with stress level equal to the endurance limit. This theoretical lifetime is twice the median value of N corresponding to a loading of constant amplitude under the high stress level alone. We can conclude that the stress equal to the endurance limit participate to damage if damage is initiated by higher stress levels than the endurance limit.

CONCLUSION

Random fatigue tests have been performed on a spheroidal graphite cast iron under spectrum loadings varying in equi-probable blocks. The distribution of the lifetime can be described by a log-normal distribution. In case of a large number of blocks with many stress levels, the apparition order of these stresses does not seem to be a significant factor in Torsion and in Plane Bending. Blocks equal to the endurance limit participate to damage cumulation if there are higher stress levels which initiate damage. Four cumulative damage rules have been tested. Unconservative predictions were obtained. These previsions may be partly explained by the fact that the tested rules do not take into account blocks with stress equal to the endurance limit. Further works needs to be done to understand the physical damage mechanisms in multiaxial random loading.

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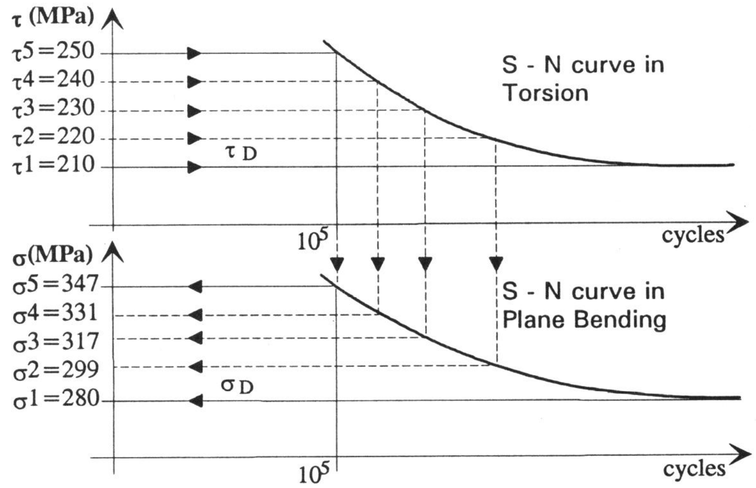

Figure 1. Choice of the stress amplitude of each block.
Relation between stress levels chosen in Torsion and in Plane Bending.

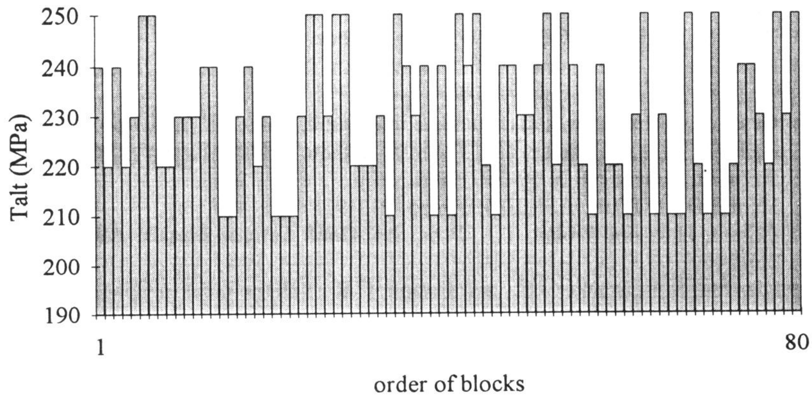

Figure 2. Example of loading spectrum in Torsion, spectrum 1 (80 blocks).

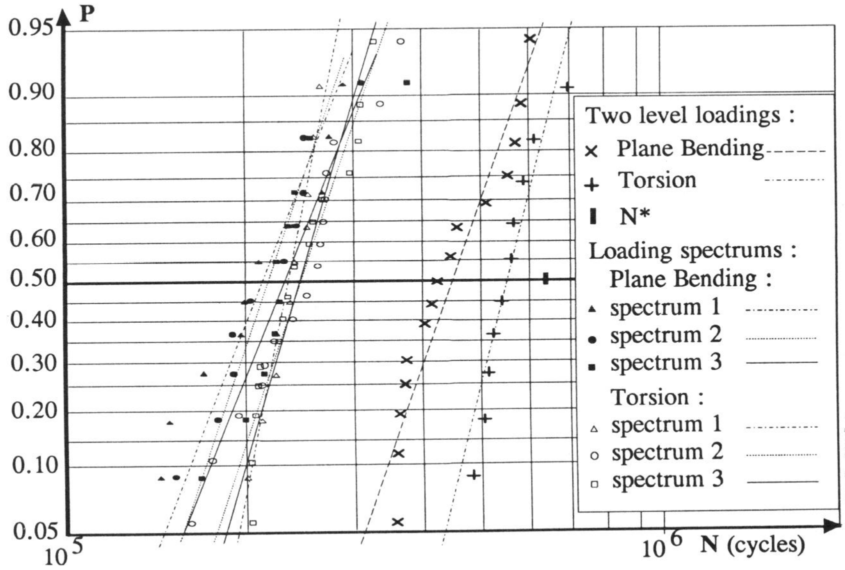

Figure 3. Test results under loading spectrums varying in blocks and under loadings with two stress levels alternatively applied until failure.