EXPERIMENTAL ANALYSIS OF FATIGUE CRACK GROWTH LIFE UNDER RANDOM LOADING

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ABSTRACT

In order to analyse the fatigue crack growth under random loading and to have enough data to analyse the behaviour of some crack growth models, a total of 170 crack growth tests under stationary random loading have been carried out. All these tests can be grouped in eight different series. The statistical parameters of the loading histories used for each series of tests were maintained, changing these parameters from one to another series. The loading histories used for each test into the same series were different but with the same statistical parameters. Using these test data, different analyses of the fatigue behaviour and of the models to analyse the crack growth under random loading have been done. These analyses include aspects such as the effect of the length of the loading histories, their loading level, and the bandwidth of the random loading process. The strip yield model proposed by Newman, adding some small modifications, has been used to simulate the crack growth behaviour of the 170 tests. A statistical model to calculate the expected fatigue life has been developed. The results of the strip yield and the statistical models compare nicely well with experimental results.

INTRODUCTION

The prediction of the fatigue crack growth life under random loading is a difficult task due to the large number of variables involved in the process, many of which are random variables. Among all the random variables that influence the fatigue crack growth life, some of them are specially significant, such as: the initial crack length [1-3]; the crack growth behaviour, which is simulated through random parameters that define the crack growth law [4,5]; the fatigue crack growth threshold (ΔK_{th}); or the load variation [6-8].

The random characteristic of loading process prevents the real knowledge of the loads, which can only be defined statistically. In case of random loading, the use of different load records equally representative of the same random loading process may result in very different crack growth lives, regardless they are obtained by test or simulation.

To analyse the fatigue life of any mechanical system under random loading, either by testing or simulation, a load history representative of the random process is generally applied repeatedly to the system until failure takes place. The load record used to simulate the random process will be one of the many load histories that can be used as statistically representative of the process. If the test or simulation is carried out using a different representative load record, the fatigue life obtained will be different from the one produced using the first load history. This difference in the obtained results will depend on the characteristics of the material, the statistical characteristics of the load and on the length (number of cycles) of the representative load records used.

The use of a finite length load record, which is repeated as many times as needed until the fatigue failure, may be a source of errors. The repetition of the same load record introduces an artificial sequence effect. The influence of this sequence effect will depend on several parameters, one of which is the length of the record [9]. Also, the load history used is not just a sample of the random loading process: another representative but different load history will produce a different fatigue life of the system. Thus, the fatigue life obtained by testing or simulation with one of these load histories will not be just one of the possible ones. It is not known whether it is close or far to the minimum or the average of all possible results. To get reliable estimations of the fatigue life under real loads by using representative loading records, the possible variation of the results produced, as a function of the representative record used must be know. It is important to know whether the fatigue life obtained with a representative load record is close to the expected real one or not and an estimation of the scatter of the fatigue life that will be produced when different load histories are used.

In previous works carried out by the authors [9,10], using numeric simulation of the crack growth process under random loading, the influence of the bandwidth of the random loading process and of the length of the load record were analysed. In this work, an experimental analysis of the effect of the same parameters is presented. Results of 170 tests are shown. These 170 tests are grouped in eight sets. Each of them differs from the others on the bandwidth of the random loading process, the load level or the length of the load records used to simulate the loading process. The influence of these parameters on the fatigue life obtained is analysed. Also, the reliability of the strip yield model proposed by Newman [11], and that of a statistical model proposed by the authors of this paper [12], to predict the fatigue crack growth life are analysed. This analysis is carried out by comparison of the experimental and the simulated results.

TESTS

Each of the 170 tests has been performed applying a finite length load record, which has been repeated indefinitely until fatigue failure. Tests have been grouped in eight different series (S1 at S8). All tests of each series were carried out using load histories generated from the same zero mean stationary gaussian random loading process, defined by its power spectral density function (*psd*). Power spectral densities with four different bandwidth were used. For three of these bandwidths, power spectral densities with two different load levels, defined by the mean square, have been used. For one of the bandwidths, only one load level was used. Also, for one of the *psd* defined, two different series of tests were performed: one using loads histories including 5000 cycles and another with load histories containing 25000 cycles. The bandwidth has been characterised by the irregularity factor ε, defined as the relationship between the frequency of crossings of the mean value with positive slope and the frequency of peaks. The irregularity factor varies between 0 and 1, increasing the width of the band as ε goes from 0 to 1. The irregularity factor, ε, of the processes used in this work have been: 0.64, 0.70, 0.77 and 085.

For every test series, except for S1, 20 different zero mean load histories containing 25000 cycles have been numerically simulated. For the series S1, the *psd* used to generate the load histories was the same as for series S4; the number of load histories generated was 30 and the number of cycles of each history was 5000. The shape and the parameters defining the *psd*´s used here are the same of those with the same irregularity factors defined in a previous work [10]. The two load levels were characterised by their mean square. The root mean square of these two levels were 1080 N, for the highest load level, and 640 N, for the lowest load level. Once every load record was numerically obtained, a positive 4850 N constant load was added to avoid the existence of compressive loads during the test. Table 1 shows the characteristics of the load records used for each series. Note that after adding the constant load, what was defined as the root mean square of the record is transformed into the standard deviation, σ.

Each one of the 170 generated load histories has been applied to a different test specimen, and the crack growth has been measured by using an alternating current potential drop (ACPD) measuring system. The material used in the tests has been 2024-T351 aluminium alloy. The test specimens have been of the Compact Tension (CT) type, with a thickness of 12 mm and 50 mm wide. To produce the same initial conditions in all tests, all specimens have been pre-cracked by applying the same constant amplitude cyclic load until getting a 15 mm initial crack length. After the initial crack length was obtained in each specimen, the random loading test started and the crack growth was followed until the crack reached a length of 25.3 mm. Detailed information of the test procedure can be found in [13].

TABLE 1

STATISTICAL PARÁMETERS OF THE LOAD RECORDS USED IN TESTS

Series	Irregularity factor, ε	St. deviation of load, σ (N)	Records length (cycles)	Number of records
S1	0.77	1080	5000	30
S2	0.64	1080	25000	20
S3	0.70	1080	25000	20
S4	0.77	1080	25000	20
S5	0.85	1080	25000	20
S6	0.64	640	25000	20
S7	0.77	640	25000	20
S8	0.85	640	25000	20

RESULTS AND DISCUSSION

The influence of the bandwidth, length of the load history and stress level are analysed through the comparison of several statistical parameters of the lives obtained for each test series. The effect of these characteristics of the load histories on the mean life, μ, and on the fatigue life scatter produced for each test series will be analysed. The scatter in each series is characterised by standard deviation, σ, of the fatigue lives obtained for the test in the series. Table 2 shows the values of these statistical parameters, the coefficient of variation (COV) of the fatigue lives obtained for each series and the coefficient of correlation, ρ, between the highest five peaks of the records and the lives that they produce. This parameter will be introduced later on in this paper.

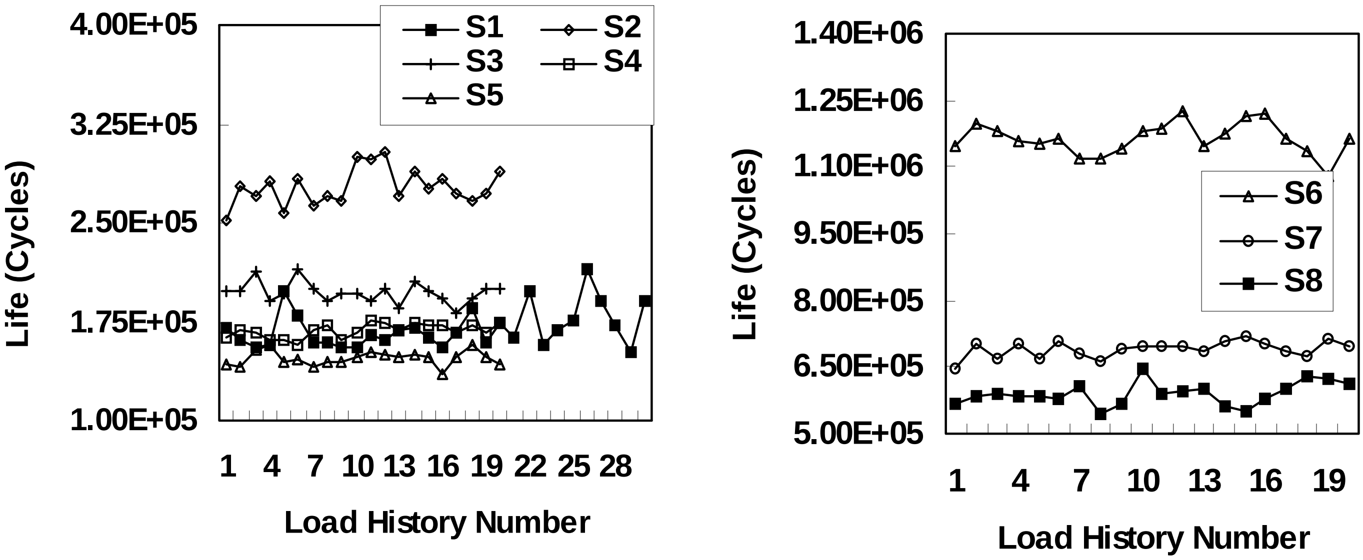
TABLE 2

STATISTICAL PARAMETERS OF THE TEST RESULTS

Series	S1	S2	S3	S4	S5	S6	S7	S8
μ	169978	277151	197114	168287	146981	1163986	690667	589569
σ	15272	13377	7686	5124	5363	35447	17715	24525
COV	0.0898	0.0483	0.0390	0.0304	0.0365	0.0305	0.0256	0.0416
ρ	--	0.84	0.66	0.58	0.77	0.64	0.12	0.4

Fatigue life scatter

Figure 1 shows the crack growth lives obtained in the 170 tests: Figure 1(a) shows the results of the five series carried out with the highest load level and Figure 1(b) for the four series with the lowest load level. The values corresponding to each series of tests are shown connected by lines. Regarding the tests results corresponding to series S1 and S4 (Figure 1(a)), which use load records with different lengths but representative of the same process, it can be seen that the fatigue life results for these two series are similar. The mean lives obtained in both series are very close. However, the scatters of lives obtained for each series are very different: the coefficient of variation (COV = σ_{life}/μ_{life}) produced in series in S1 is three times the value obtained in series S4. The decrease of the fatigue life scatter with the increase of the length of the load records applied is due to two reasons. It is well known that the highest peaks of load have the largest influence on the fatigue crack growth because of the sequence effect. In case of short load histories, the number of peaks with a predominant effect on the crack growth rate is small, and the statistical distribution of this group highest peaks has a larger scatter than the general distribution of peaks. The other reason is associated to the previous one: the repetition of the load record indefinitely until failure introduces an artificial sequence effect due to the periodic repetition of the load record. Short load records allow the effects of an overload to persist during the next repetition of the record, producing a sequence effect, which in some cases could be active until the same overload is produced during the new repetition of the record. This effect will be reduced as the length of the load histories increases. In the series S1 and S4, the correlation between the fatigue lives obtained in each test and the value of the maximum overload of the record used has been calculated. The coefficients of correlation, ρ*, obtained in each case where 0.96, for series S1, and 0.52, for series S4. These values confirm the great influence that the length of the representative load history used to simulate a random loading process has on the fatigue crack growth life obtained by test.



(a) (b)

Figure 1: Results of the 170 tests, grouped by series: (a) highest load level series; (b) lowest load level.

Regarding series S2 to S5, and S6 to S8, Table 2 and Figure 2(a) show the evolution of the coefficient of variation (COV) of fatigue lives of each series with the bandwidth of the random loading process used. This parameter tends to decrease as the process bandwidth decreases, increasing again when the band is very narrow. Table 2 shows also for each series the coefficient of correlation, ρ, between the fatigue lives obtained in each test and the average value of the five highest peaks of the record used in the test. This parameter gives an idea about the effect of a very small number of cycles of the load record on the fatigue life: a large value of ρ means that the five largest peaks of the load records have a very high influence on the fatigue life because of the fatigue crack growth retardation produced. It can be seen in Table 2 that COV and ρ have a similar trend with the bandwidth. This trend can be explained considering that when the value of ρ is high, a very small number of cycles have a large influence on the fatigue life. For low correlation there is not a so high effect of a small number of cycles. Considering the average of the five highest peaks of each record as a new parameter, the scatter of this average in each series of record will be much larger than the scatter of other statistical parameters usually related to the fatigue life. So, if the influence of this small number of peaks increases (ρ increases), the COV of the fatigue lives obtained in a series will also increase. The same effect was found by the authors using numeric simulations [10].

Mean fatigue life

The bandwidth of the random loading process has also a large effect on the mean of the fatigue lives of each series. Figure 2(b) shows the variation of the mean fatigue life versus the irregularity factor for series S2 to S4. The mean life of the specimens decreases when ε increases (the bandwidth decreases). This trend is the same for both loading levels, as can be seen in Table 2. An explanation of this phenomenon is that, in a group of stationary random processes with the same mean load and standard deviation and different bandwidth, the mean of load peaks and ranges increases as the bandwidth decreases. From the data in table 2 and Figure 2(b), an expression, which relates the mean life of a series to some statistical parameters of the random loading process, has been fitted:

$$\mu_{ij}\varepsilon_{1.5j}^{2} = D_i \tag{1}$$

where, the subscripts *i* and *j* represent the load level and bandwidth of the series, respectively, μ_{ij} is the mean fatigue life of series with load level *i* and bandwidth *j*, and D_i is a constant, obtained experimentally for each load level. The parameter $\varepsilon_{1.5}$ is defined as:

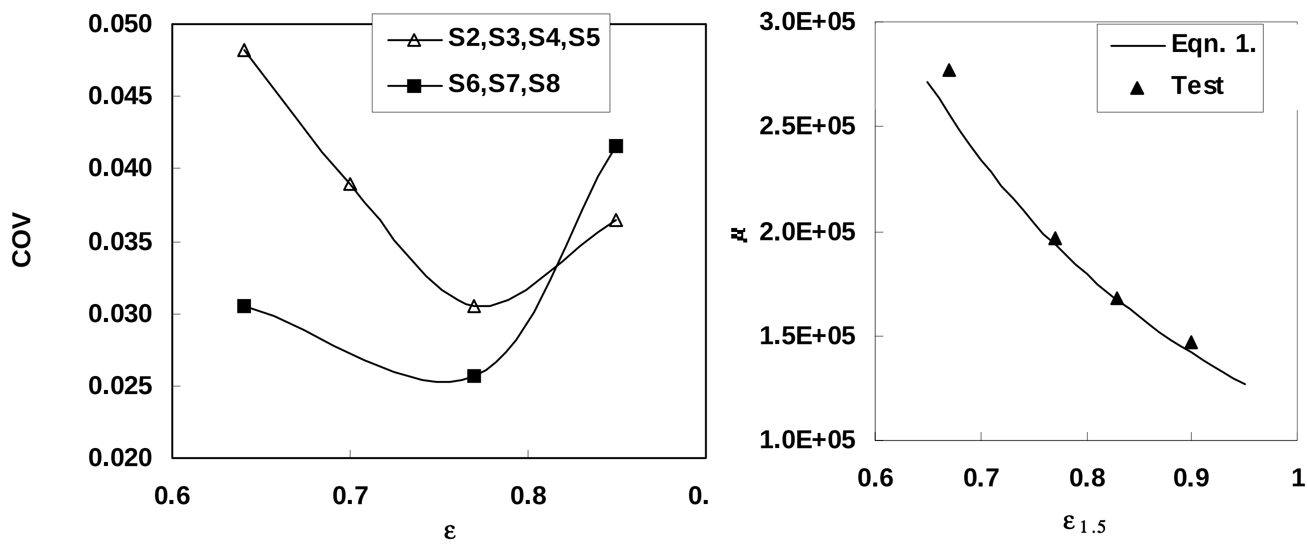
$$\varepsilon_{1.5} = \frac{M_{1.5}}{\sqrt{M_0 M_3}} \tag{2}$$

where

$$M_n = \int_{-\infty}^{\infty} \omega^n S(\omega) d\omega \tag{3}$$

ω is the frequency and $S(\omega)$ the *psd* of the original zero mean loading process.

From the experimental data, the parameter D_i has been calculated using equation (1) for series *S4* (D_1) and *S7* (D_2), both with an irregularity factor $\varepsilon = 0.77$. This value has been used to estimate, using equation (1), the mean fatigue life produced in all other experimental series. Figure 2b shows the values μ_{ij} obtained with equation (1), compared with the experimental results. Estimates of the mean lives are all inside the band ±8%. Table 3 shows the ratios between the results obtained with equation (1) and the tests results. If this kind of fitting could be generalised to other random processes and materials, it would be an interesting tool. An estimation of the fatigue crack growth life under any type of random loading process could be done by extending the mean life produced under another random loading process with the same mean and standard deviation of loads.



(a) (b)

Figure 2: Evolution of the COV and the mean fatigue life with the bandwidth: (a) COV; (b) mean fatigue life, μ, for series S2 to S5.

Simulations

In order to check the reliability of some fatigue crack growth simulation methods, the same load records used for testing have been used to simulate the fatigue crack growth process. The 170 load records have been applied to the cycle-by-cycle simulation scheme proposed Newman [11]. Lives estimated by simulation compare very well to the experimental results. Scatter and mean value of lives obtained in each series by simulation are close to those obtained by tests [14]. The same random loading processes have also been used to estimate the mean fatigue life of each series by a statistical model which includes the retardation effect proposed by the authors [12]. This model is unable to estimate the scatter, but it produces reliable estimations of the mean life of each series. It uses as data the probability density function of peaks in the stationary random loading process, which can be obtained from its mean and power spectral density.

TABLE 3
RELATION BETWEEN MEAN LIVES OBTAINED BY TESTS AND BY EQUATION (1)

Series	S2	S3	S4	S5	S6	S7	S8
$\mu_{eq.(1)} / \mu_{test}$	0.93	0.97	-	0.97	0.92	-	.99

Figure 3 shows a comparison of the experimental results with those obtained by simulation for one of the series (*S1*). The experimental and cycle-by-cycle simulation results are shown for every test in the series. The mean life of the series is also shown. It is represented with a horizontal broken line. For the statistical model, the estimated mean fatigue life of the series is also represented with a solid line. It can be seen that both models give fairly good estimation of the mean life, and that the cycle-by-cycle Newman's model estimates also very well the scatter produced by using different load records.

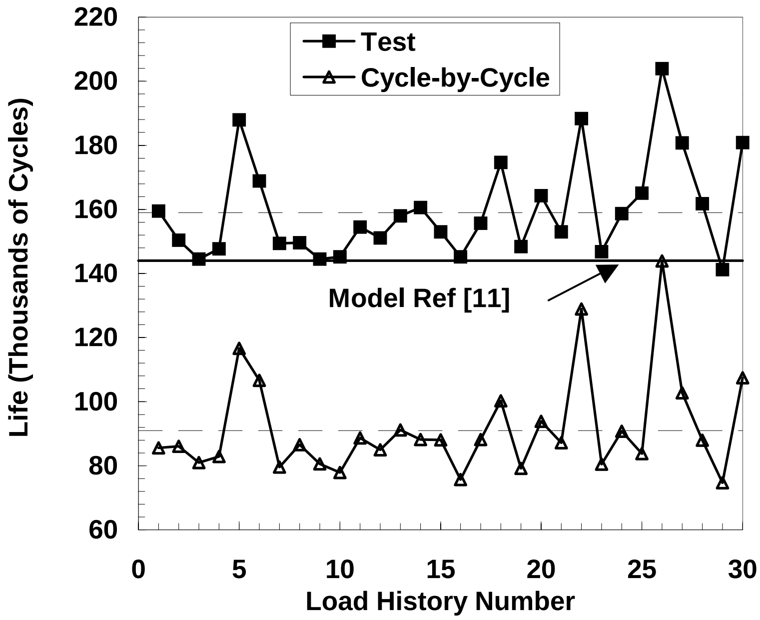


Figure 3. Fatigue crack growth lives obtained by tests and simulations.

CONCLUSIONS

This work provides new experimental data of fatigue crack growth in aluminium alloy 2024-T351 specimens under different stationary random loading processes. Results for two different load levels and four bandwidths of the random loading process are included. These data may be very useful to check new simulation schemes. The results shown are also a contribution to estimate the influence of the length of the loading record used in simulation or tests on the fatigue life results. From the data discussed in the paper, the following conclusions can be obtained:

(a) The length of the load record to be used in simulations or tests is a fundamental factor, which must be defined before the analysis of the fatigue life under random loading. For any random loading process, the reduction of the number of cycles in the loading history to be applied increases substantially the scatter of the lives obtained with different trials.

(b) The length of the record does not affect the mean life obtained in a series of tests.

(c) The influence of the random loading process bandwidth on the scatter is important. This effect is related with the effect of overloads on the fatigue life. However, this effect will decrease as the length of the load records increases. It would be interesting to carry out series of tests with records having more than 25000 cycles to get a better knowledge of the effect of the length and bandwidth on the scatter.

(d) The influence of the extreme value of the load record depends strongly on the number of cycles of the record. However, as far as the cases studied is concerned, this dependence is affected by the bandwidth of the random process.

(e) The mean life depends strongly on the bandwidth of the process.

(f) For stationary random processes and materials used in this work, the mean crack growth life is related with $\varepsilon_{1.5}$. The experimental estimates of the mean life produced for a load level and bandwidth can be used with equation (1) to estimate the mean life for another random processes with the same load level but different bandwidth.

(g) The data obtained in the test series performed are a very useful to check the reliability of fatigue crack growth models.

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