CALENDAR FATIGUE LIFE OF AIRFRAME MATERIALS

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Abstract

A long-term program to study the calendar fatigue property of airframe materials has being carried on. The specimens of several kinds of material were exposed to an atmospheric environment and planned to do fatigue test after being exposed for 0~15 years. This paper presents the result of the first 4 years.

The relation between the fatigue properties and the exposure calendar time is analyzed thoroughly. An approach to predict the calendar fatigue life of structure is developed.

Some conclusions are: (1)The mean and the variation coefficient of fatigue life decreases and increases with the elapse of calendar time respectively. (2)The effect of cold expansion to prolong the fatigue life of a hole decreases with the calendar time. (3)Applying a modified Miner' rule to predict the calendar fatigue life of a structure is practical. (4)It is not correct to use the ordinary fatigue property of material without any deduction to predict the fatigue life over a certain calendar time.

1 Preface

Besides the traditional two fatigue criteria of aircraft (flight hours and number of flights), a third criterion is recently demanded: the service calendar life of aircraft. During the service time, the fatigue strength of structural material decreases continuously. When predicting an aircraft fatigue calendar life, this decrement should be taken into account.

Usually the accelerated corrosion fatigue test is conducted in laboratory to obtain the fatigue strength decrement [1][2]. But (1)the corrosion environment can not simulate the real atmospheric environment properly; (2)can not give out the equivalent calendar time as the specimen exposed to the real atmospheric environment; (3)can not involve the aging effect of materials. What is more, the military aircraft spends over 90% of its service time staying on the ground. So the decrease of the fatigue strength under the ground condition is required.

In order to evaluate the service calendar life of the aircraft structure properly, A 15-year-program to study the calendar fatigue property of the airframe materials has being carried on. Here a research of 4 year result is presented.

2 Experiment

2.1 Specimen

The specimens are made of three kinds of material: hard aluminum alloy LY12CZ, high strength aluminum alloy LC4CS and high strength steel 30CrMnSiNi2A. Each material is machined into three types of specimen: type(I) plain-plate without hole, type(II) central-hole-plate(CH) and type(III)cold-expansion-hole-plate(ECH)(Fig.1).The holes for LY12CZ specimens are filled with over sized Hook Bolts.

All the specimens are heat treated and

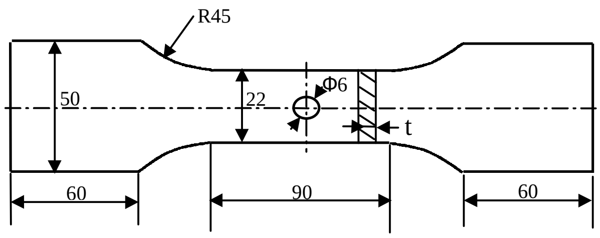

Fig.1: The central-hole specimen (for LC4CS t=4,for 30CrMnSiN2A t=7;dimension in mm)

surface protected as same as the corresponding structural parts, i.e. aluminum specimens are anodized and painted, and the high strength steel specimens are phosphorated and painted.

2.2 The atmosphere exposure test

The atmosphere exposure test site is 350m off the sea and 12.3m above the sea level. The typical yearly average value of water deposit is 198mm and the pH value of the rainwater is 5.1. The specimens were put in a shed to simulate the inner structural details of aircraft[3]. They are divided into seven groups and planned to do fatigue tests after being exposed to the environment for 0, 1, 2, 4, 7, 10 and 15 years.

2.3 Fatigue test

A block loading spectrum is used for LY12CZ specimens group. A constant-amplitude loading spectrum is applied to the other two groups(CH and ECH specimens). The stress ratio is 0.06, σ_{max}=300MPa and 800MPa for LC4CS and 30CrMnSiNi2A specimens respectively. The plain plate specimens are tested for obtaining S—N curves.

3 Analysis and discussion

To investigate the decreasing of fatigue strength, a parameter 'life ratio' R is introduced. The ratio R means: at the same testing condition, the fatigue life of a treated material compares with the fatigue life of original material at 0 year.

$$R = \frac{\textit{fatigue life of treated material at present}}{\textit{fatigue life of original material at 0 year}}$$

Some typical curves of R against calendar year are shown in Fig.2~Fig.4.

3.1 The statistical property of fatigue life

(1) The fatigue life data can pass the log-normal distribution examining with coefficient of linear correlation within 0.80~0.979.

The mean of fatigue life decreases with the elapse of calendar time(Fig.1a and Fig.2a), and the coefficient of variation(Cv) of fatigue life increases with the elapse of calendar time[4] (Fig.1b and Fig.2b.).

(2) The R-y curves for EH-specimens and ECH-specimens are different. For EH-specimens, the curve drops down gradually and very slowly and is almost a straight line. The fatigue life of a cold-expansion hole increases significantly, the R ratio at 0 year can even rise up to 2~3. But during the calendar year elapse, the R ratio drops down rapidly at the beginning of the service time. Then the decreasing tendency becomes flat. The shape of the curve is like 'a chair'. The test result shows that the

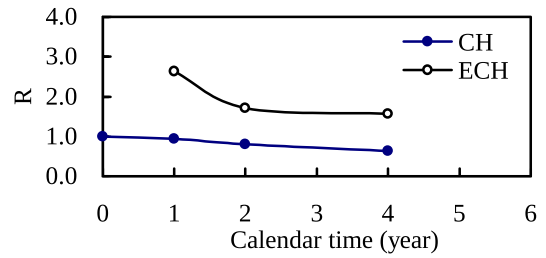

Fig.1a: R-y curve for LC4CS specimen

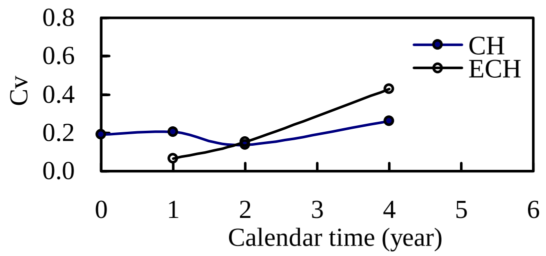

Fig.1b: Cv-y curve for LC4CS specimen

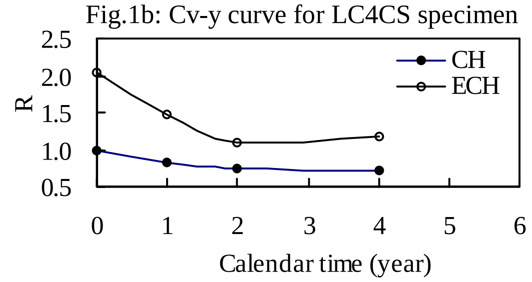

Fig.2a: R-y curve for 30CrMnSiNi2A specimen

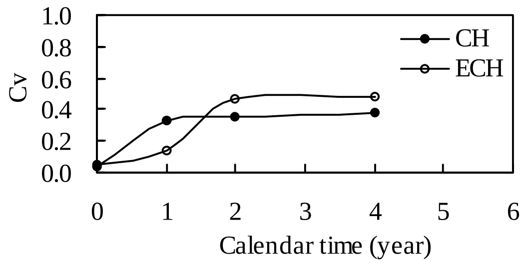

Fig.2.b: Cv-y curve for 30CrMnSiNi2A specimen

R ratio of ECH at 2 years is approximately equal to that of CH at 0 year. Even so, the R ratio of ECH is always greater than that of CH.

3.2 $y-S-N_f$ curve for plain specimen

Within the range of middle fatigue life, the $S-N_f$ curve can be fitted to:

$$N_f \cdot S^m = C \qquad (1)$$

Fig.3 shows the fitting $S-N_f$ curves at 0,1,2 and 4 year. From the $S-N_f$ curves for LC4CS (Fig.3a), the $R-y$ curve at each stress level can be obtained (Fig.4a). The $R-y$ curves at all the five stress levels are rather flat. That means there is a weak correlation between the life ratio R and the stress level, So, the R-y curves for LC4CS at all stress levels can be fitted to one curve (Fig.4b):

$$R = 1.0028e^{-0.1694 \cdot y} \qquad (2)$$

Then, at stress level S_i, the fatigue life at the calendar year y is:

$$N_{fi}(y) = R \cdot N_{fi}(0) \qquad (3)$$

where $N_{fi}(0)$ is the fatigue life at 0 year at S_i. So, $y-S-N_f$ curve for LC4CS can be in the following form:

$$R = 1.0028e^{-0.1694 \cdot y} \cdot N_f(0) \cdot S^m = C \qquad (4)$$

where m and C are parameters at 0 year.

The $S-N$ curves for 30CrMnSiNi2A at 1,2[5] and 4 year almost coincide in one curve, then for these curves: m =2.97831, C = 6.97378×10^{12}.

4 The calendar fatigue life predicting approach

When a structure of aircraft is subjected to a block of loading spectrum of k stress levels (T flight hours), according to the Miner ruler, its predicted fatigue life is :

$$T \Big/ \sum_{i=1}^{k} \frac{n_i}{\overline{N}_{fi}} \text{ (flight hours)} \qquad (5)$$

where n_i and $\overline{N}_{fi}$ are loading cycles and the fatigue life at the i stress level S_i. When an aircraft serves in a corrosion environment, and it can accomplish a loading spectrum of T flight hours training within an elapse of calendar time Y, then [6]:

$$\sum_{j=1}^{L} \Big(\sum_{i=1}^{k} \frac{n_i}{\overline{N}_{fi}(jY - Y + y_i)} \Big)_j = 1 \qquad (6)$$

where y_i is the corresponding calendar time at

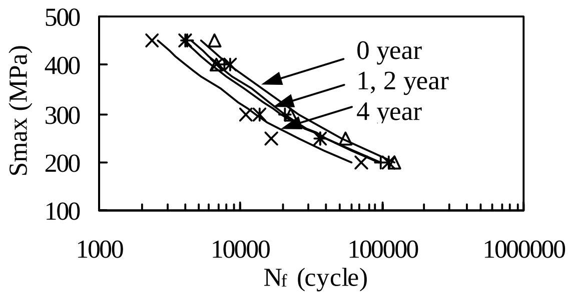

Fig.3a: S-N curve for LC4CS plain specimen

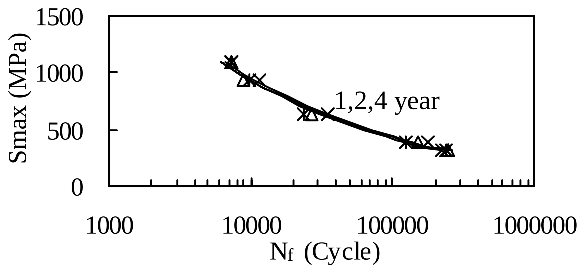

Fig.3b:S-N curves for 30CrMnSiNi2A plain specimen

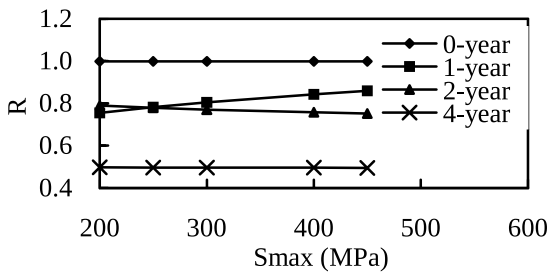

Fig.4a: R-Smax curve for LC4CS plain specimen

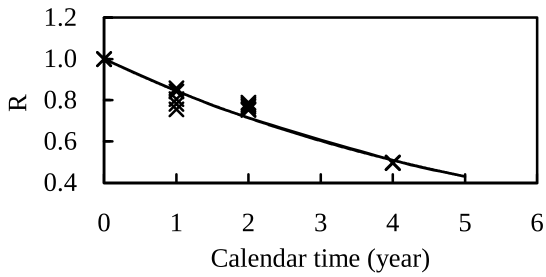

Fig.4b: R-y fitting curve for LC4CS plain specimen

S_i, $\overline{N_{fi}}(jY - Y + y_i)$ is the fatigue life of material for the i stress level at the calendar time $(jY - Y + y_i)$, and L is the loading blocks. So, the calendar fatigue life of the structure is $L \cdot Y$.

Generally, an aircraft structure serves in several different regions (with different atmospheric corrosion environment) such as D_1, D_2, $\cdots D_p$ (Fig.5), and the elapse of service calendar time in these regions are Y_1, Y_2, $\cdots Y_p$ respectively. The structure is subjected to k_1, k_2, …k_p stress levels of loading spectrum in the corresponding region. y_{1i}, y_{2i}, $\cdots y_{pi}$ are the calendar time at i stress level during the service time in each region. Then the modified Miner rule is:

$$\sum_{i=1}^{k_1} \frac{n_i}{\overline{N_{fi}}(y_{1i})} + \sum_{i=1}^{k_2} \frac{n_i}{\overline{N_{fi}}(y_{2i})} + \cdots + \sum_{i=1}^{k_p} \frac{n_i}{\overline{N_{fi}}(y_{pi})} = 1 \qquad (7)$$

Usually, $R-y$ curves of material (see 2.1 and 2.2) can be in such fitting function as:

$$R_1 = f_1(y_1),\ R_2 = f_2(y_2), \cdots, R_p = f_p(y_p)$$

Let $R_1 = R_2 = \cdots = R_p$, then certain relationship among $y_1, y_2 \ldots y_p$ can be obtained:

$$y_1 = \boldsymbol{\alpha}_2 y_2 = \cdots = \boldsymbol{\alpha}_p y_p \qquad (8)$$

where $\boldsymbol{\alpha}_2, \boldsymbol{\alpha}_3$, $\cdots \boldsymbol{\alpha}_p$ are the equivalent coefficient among the calendar time of the different regions. Taking the region D_1 as the reference region, then $\overline{N_{fi}}(y_{1i})$, $\overline{N_{fi}}(y_{2i})$, $\cdots \overline{N_{fi}}(y_{pi})$ in formula (7) are:

$$\overline{N_{fi}}(y_{1i}) = f_1(y_{1i}) \cdot \overline{N_{fi}}(0),$$

$$\overline{N_{fi}}(y_{2i}) = f_1(Y_1 + \boldsymbol{\alpha}_2 y_{2i}) \cdot \overline{N_{fi}}(0),$$

……,

$$\overline{N_{fi}}(y_{pi}) = f_1(Y_1 + \boldsymbol{\alpha}_2 Y_2 + \cdots + \boldsymbol{\alpha}_{p-1} Y_{p-1} + \boldsymbol{\alpha}_p y_{pi}) \cdot \overline{N_{fi}}(0) \qquad (9)$$

where $\overline{N_{fi}}(0)$ is the fatigue life at i stress level at 0 year. So, formula (7) can be simplified as:

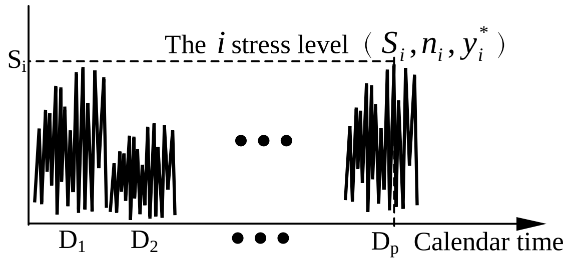

Fig.5: Calendar loading spectrum of aircraft

$$\sum_{i=1}^{k} \frac{n_i}{f_1(y_{1i}^*)\overline{N_{fi}}(0)} = 1 \qquad (10)$$

where $y_{1i}^* = Y_1 + \boldsymbol{\alpha}_2 Y_2 + \cdots + \boldsymbol{\alpha}_{p-1} Y_{p-1} + \boldsymbol{\alpha}_p y_{pi}$ are the equivalent calendar time in a new re-arranged sequence.

5 Conclusion

On basis of above research, some conclusions can be made as following:

(1) The fatigue life of materials follows log-normal distributions or two-parameter-weibull distributions.

(2) The mean of fatigue life decreases with the elapse of calendar time, and the deviation increases with the elapse of calendar time. The coefficient of variation of fatigue life then increases with the elapse of calendar time.

(3) Fatigue stress-life curves ($S-N$ curves) change with pre-corrosion calendar time. At different stress levels, the curves of fatigue life decrease against the elapse of calendar time($R-y$ curves)can be fitted to one curve.

(4) The effect of cold expansion to prolong the fatigue life of a hole decreases significantly with the calendar time.

(5) It is practicable to apply the modified Miner rule as well as introducing calendar time for predicting the calendar fatigue life of airframe material.

(6) It is not correct to use the ordinary material fatigue strength (here is the ‘0-year’ strength) without any deduction to predict fatigue life over a certain calendar time. Usually the predicted (by testing or by calculation) fatigue life will be divided by a safety coefficient 3~4 to obtain a much smaller service life. Such a coefficient could only be an empirical value,

but as for considering the corrosion and aging it has no sound basis.

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