# Life prediction model of Aircraft Structure under corrosion Environment

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## Abstract

A new concept named Aircraft Structural Life Envelop is presented and its development method is described. Experiment of lap-joint specimens of 7B04 aluminum alloy under alternate action of corrosion and fatigue was carried out in this paper to simulate the service progress of aircraft and validate the exactitude of ASLE. The ALSEs of four service areas were build. The test results prove that the ALSE build by experiment under alternate action of corrosion and fatigue has a high precision and the potential service life of aircraft can be used plenarily.

## 1. Introduction

Aluminum alloy has been widely used in aero plane for the purpose to reduce the weight of the structure. In reality, the structural life of an aircraft is affected by its in-service environment, which relates specifically to issues of corrosion and cyclic loading. It has been wildly accepted that the damage of corrosion will reduce the efficient area of section and weaken the tolerance of the material for the damage and make great threaten to the flight safety. Most of studies about corrosion focused on pre-corrosion and corrosion fatigue, while less took the real service progress into consideration. When the aircraft flight above 3Km, the corrosion environment is minimal, for example slat, temperature, moisture and so on, while the fatigue load due to lift force, maneuver, flutter etc. is maximal. And when the aircraft is on the ground, the corrosion progress is maximal, while flight load and vibration are not existent. So fatigue progress and corrosion progress are alternate action of corrosion and fatigue during the service progress of aircraft. Some investigations had been done to investigate the difference between alternate action of corrosion and fatigue and pre-corrosion fatigue. Meana and Henaff [1-2] found the difference between alternate immersion corrosion and pre-corrosion in research of the affection of frequency and salt solution on crack growth of 2024 aluminum alloy. M.L. Du and Chen [3] found that the fatigue life of 2024 and 2A12 aluminum alloy specimens in "fatigue + corrosion + fatigue" mode was longer than pre-corrosion specimens under same corrosion condition. Some US Military Standards, such as MIL-A-8860B, MIL-STD-1573, etc., took corrosion into aircraft production and usage process. The aircraft service life will be wasted if we administer service life using pre-corrosion rule. In China, there are two indices to limit the aircraft structural service life, they are fatigue life (usually expressed as flight hours) and calendar life (expressed as service years). But the fatigue life limit and calendar limit are usually not matched very well, this may result in huge waste of aircraft structural life potential or lead some structures in unsafe states [4-5].

So it is very necessary to study the materials' characteristics under alternate function of corrosion and fatigue to make exact life prediction of the airplane in service. In this paper, a new life prediction method was put forward using a life scope of fatigue life and calendar life, and naming it the Aircraft Structural Life Envelop (ASLE). The alternate experiments of corrosion and fatigue using lap-joint specimens of 7B04 aluminum alloy were taken out to create ASLE and validate the exactitude of ASLE.

## 2. Concept of Aircraft Structural Life Envelop

ASLE is a safe and reliable life scope for aircraft structures in service. It can be described in a two-dimensional Cartesian coordinate, using the fatigue life as the vertical axis and the calendar life as the horizontal axis. The ASLE reflects the interrelationship between limits of fatigue life (Nf, in flight hour) and calendar life (Ny, in years). When an aircraft is used so heavily that it exceeds the limit of ASLE, the structural state is considered to be unsafe. That is to say, the flight envelop [6-8] ensures the safety of each flight of an aircraft, while the ASLE ensures the safety of an aircraft throughout its service life.

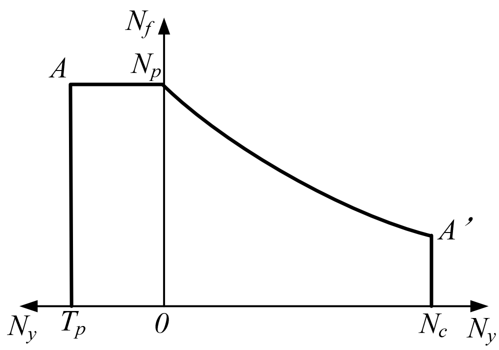



Fig. 1 Typical ASLE of an aircraft grounded in one environment

Fig. 1 shows a schematic diagram of typical ASLE. It only describes the life limits of an aircraft grounded in one environment. In this diagram, both directions of the horizontal axis (Ny) are positive; they are calendar lives under different states of protective coating. The abscissa value of Tp is the effective period of protective coating; structures can be considered to be suffering from pure fatigue damage in this period. The point Np represents the fatigue safe life with high reliability in the condition of no corrosion. This parameter can be obtained through component or full-scale fatigue tests and through reliability analyses. The curve Np-A' reflects change laws of the fatigue safe life of structures in the corrosive environment without the protection of protective coating and can be expressed by *C-T* equation.

Any point on the C(T) curve can be determined by Eq. (1)

$$C(T) = \frac{N_{99.9}(T)}{N_p} \tag{1}$$

Where $N_p$ is the fatigue safe life under the baseline load spectrum without corrosion, $N_{99.9}(T)$ is a fatigue safe life with reliability 0.999 and confidence 0.9, after equivalent $T$ years' accumulate corrosion.

$$N_{99.9} = 10^{\overline{X} - K * S_T} \tag{2}$$

$$\overline{X_T} = \frac{1}{n}\sum_{i=1}^{n} \lg N_i(T) \tag{3}$$

$$S_T = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(\lg N_i(T) - \overline{X_T}\right)^2} \tag{4}$$

Where $\bar{X}_T$ is the logarithmic average of the equivalent fatigue life of the specimens under corrosion for $T$ hours, $S_T$ is the logarithmic standard deviation of the equivalent fatigue life, and k is a lower confidence limit of reliability ensuring the fatigue safe life has the reliability of 0.999 and the confidence level of 0.9. The value of $k$ is 7.1293 when the sample number (n) is 4 [27].

The $C(T)$ curve can be fitted as [24]

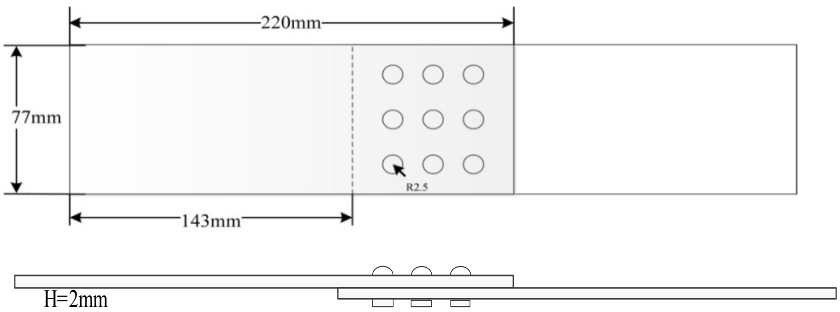
$$C(T) = 1 - aT^b \tag{5}$$

The line A'-Nc is a limit boundary to prevent an unexpected fracture of a structure due to corrosion fatigue damage. It relates to the demands of static strength and fracture characteristics in corrosive environment, and the demands of economical repair of aircraft etc.

# 3. Experimental

## 3.1 Specimens

The specimens were lap-joint specimens of 7B04 aluminum alloy to simulate the practical structural of aircraft. The shape and size of the specimens is shown in Fig.1. The specimens with and without surface protection coating have same size and joint mode and the material of rivet is 2A10.



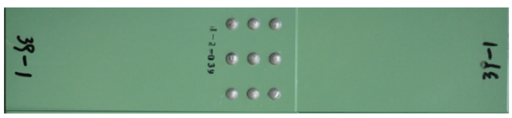



Fig. 1 The dimension of specimens

## 3.2 Experimental method

For the specimens without surface protection coating, completely reversed tension and tension fatigue test were carried out under a sine load waveform at constant cyclic stress frequency, f=20Hz. The stress amplitudes applied in fatigue test was 130MPa and the stress ratio R was 0.06. The test mode was “corrosion + fatigue + corrosion + fatigue +......until the structure failed”. For example, the specimens labeled as 1-1 were in the alternate mode: “corrosion 975 hours + 45000 fatigue cycles + corrosion 975 hours + 45000 fatigue cycles...... ”. The solution used for the corrosion investigations was made of 3.5% NaCl + $5\times10^{-5}$ M $H_2SO_4$ (PH = 4) using distilled water. The spray corrosion was taken in a YWX/Q-250 corrosion box. The experimental temperature was 40±2°C and the deposited salt spray was 2 mL/(h·80cm$^2$). We assume that the specimens subject to this corrosion environment for 32.5hours, 44hours, 70hours and 76hours respectively represent 1year service time at A, B, C, D area. The specimens were divided into two teams. One team( Ⅰ ) has five sets, while each set with different load cycles and corrosion periods to build the ASLE. The other team( Ⅱ ) has one set to simulate different flight to validate the exactitude of ASLE. The load cycles and corrosion periods of team( Ⅰ ) and team( Ⅱ ) were shown in Table 1and Table 2. The fatigue life without corrosion was also carried out at same load state. We assume that 12.5cycles represent one flight hour.

Table 1 The corrosion time and fatigue cycles of team ( Ⅰ ) in each alternate progress

| Specimen number | Corrosion time(h) | Fatigue cycles |
|---|---|---|
| 1-1 | 162.5 | 80000 |
| 1-2 | 487.5 | 60000 |
| 1-3 | 650 | 50000 |
| 1-4 | 812.5 | 50000 |
| 1-5 | 162.5975 | 45000 |

Table 2 The service progress of team ( Ⅱ )

| Service area | Flight strength (fh/a) | Service years(a) |
|---|---|---|
| A | 100 | 6 |
| B | 100 | 4 |
| C | 200 | 2 |
| A | Until structure failed | 3 |

For the specimens with surface protection coating, the accelerating environment spectrum was shown in Fig. 2. These specimens were used to determine the failure time of surface protection coating in area A, B, C and D. One cycle of the accelerating environment spectrum represent one service year in different area.

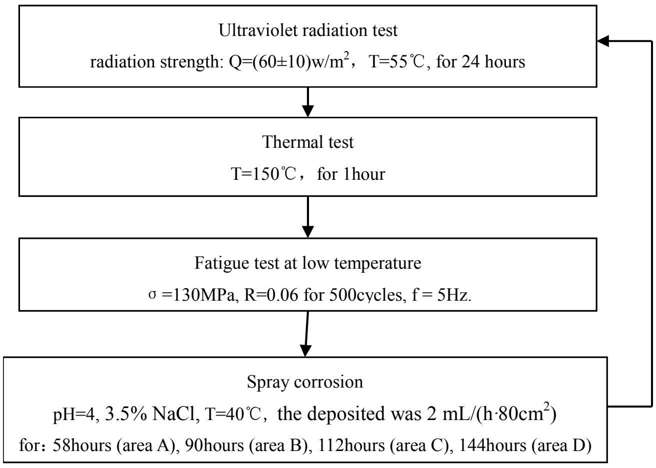



Fig. 2 The accelerating environment spectrum of area A, B, C and D

## 4. Experimental results and the building of ALSE

The test results of specimen under different condition were shown in Table 3, Table 4 and Table 5. The fatigue safe life in *C-T* function should obey log-normal distribution. Thus, Shapiro-Wilk inspection method was used to check the test result whether follow log-normal distribution.

Shapiro-Wilk inspection equation was listed as Eq. 6.

$$W = \frac{\{\sum_{k=1}^{l} \alpha_{k,n}[x_{(n+1-k)} - x_{(k)}]\}^2}{\sum_{k=1}^{n}[x_{(k)} - \overline{x}]^2} \tag{6}$$

$x_{(k)}$ is test result and $x_{(1)} \le x_{(2)} \le x_{(3)} \le x_{(4)} \ldots\ldots$, $\overline{x}$ is average fatigue life. In reference [], when n=4, if $W$>0.748, the result data obey log-norm distribution. The inspection result was shown in table 6.

Table 3 Fatigue test results without corrosion

| Specimens number | 0-1 | 0-2 | 0-3 | 0-4 | Average fatigue life |
|---|---|---|---|---|---|
| Fatigue life/cycles | 138324 | 176771 | 195420 | 134194 | 161177 |
| Flight hour/fh | 17290.5 | 22096.4 | 24427.5 | 16774.3 | 20147.2 |

Table 4 The test results of team ( Ⅰ )

| Specimen number | Fatigue life | Flight hours | Specimen number | Fatigue life | Flight hours |
|---|---|---|---|---|---|
| 1-1 | 90485 | 11310.6 | 2-1 | 110077 | 13759.6 |
| 1-2 | 113470 | 14183.8 | 2-2 | 103176 | 12897.0 |
| 1-3 | 128705 | 16088.1 | 2-3 | 77767 | 9720.9 |
| 1-4 | 151690 | 18961.3 | 2-4 | 73607 | 9200.9 |
| Specimen number | Fatigue life | Flight hours | Specimen number | Fatigue life | Flight hours |
| 3-1 | 65469 | 8183.6 | 4-1 | 87463 | 10932.9 |
| 3-2 | 93485 | 11685.6 | 4-2 | 75508 | 9438.5 |

| | | | | | |
|---|---|---|---|---|---|
| 3-3 | 94003 | 11750.4 | 4-3 | 52756 | 6594.5 |
| 3-4 | 60460 | 7557.5 | 4-4 | 60634 | 7579.3 |
| Specimen number | Fatigue life | Flight hours | | | |
| 5-1 | 68997 | 8624.6 | | | |
| 5-2 | 87102 | 10887.8 | | | |
| 5-3 | 53866 | 6733.3 | | | |
| 5-4 | 48095 | 6011.9 | | | |

Table 5 The test results of team (Ⅱ)

| Specimen number | Fatigue life | Flight hours |
|---|---|---|
| 6-1 | 72325 | 9040.6 |
| 6-2 | 103274 | 12909.3 |
| 6-3 | 103843 | 12980.4 |
| 6-4 | 96791 | 8348.9 |

Table 6 The test results of team (Ⅱ)

| Specimen set | Fatigue test without corrosion | Team (Ⅰ) | | Team (Ⅱ) |
|---|---|---|---|---|
| w | 0.8797 | 1 | 0.994 | 0.8124 |
| | | 2 | 0.8676 | |
| | | 3 | 0.8123 | |
| | | 4 | 0.9719 | |
| | | 5 | 0.9601 | |

All the test data obey log-normal distribution as shown in Table 6. So the *C*-*T* curve of different service area A, B, C and D could be fitted by least square method. The *C*-*T* equations of area A, B, C and D were listed as Eq. 7, 8, 9, 10.

The *C*-*T* equation of area A:

$$C = 1 - 0.061664T^{0.691375} \tag{7}$$

The *C*-*T* equation of area B:

$$C = 1 - 0.078993T^{0.691374} \tag{8}$$

The *C*-*T* equation of area C:

$$C = 1 - 0.089827T^{0.691375} \tag{9}$$

The *C*-*T* equation of area D:

$$C = 1 - 0.110944T^{0.691374} \tag{10}$$

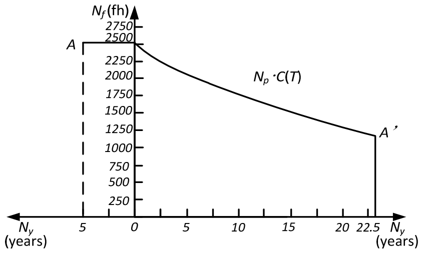
The failure time of surface protection coating was determined by measuring electrochemical impedance modulus and the test data was shown in table 7.

Table 7 The failure time of surface protection coating

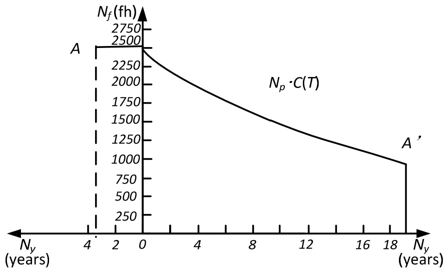
| Service area | Failure time(year) |
|---|---|
| A | 5 |
| B | 3.5 |
| C | 3 |

| | |
|---|---|
| D | 2 |

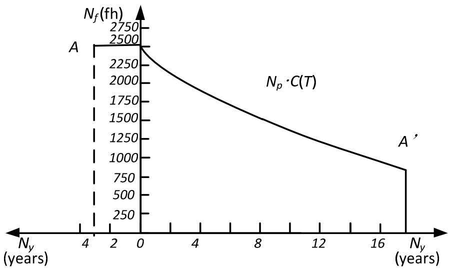
So the ALSE can be build based on the failure time of surface protection coating and *C-T* equation and as shown in Fig. 3.



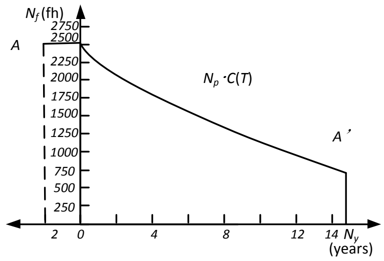

The ALSE of area A




The ALSE of area B




The ALSE of area C




The ALSE of area D

Fig. 3 The ALSE of area A, B, C, D

## 5. The inspection of ALSE

According to test results, the fatigue safe life of fatigue test without corrosion and team (Ⅱ) were calculated by Eq. (2), as listed in Table 8.

Table 8 The fatigue safe life of fatigue test and team (Ⅱ)

| | Fatigue test without corrosion | Team (Ⅱ) |
|---|---|---|
| Fatigue safe life | 3421 | 2198 |

Without the surface protection coating, the damage corresponding to different flight strengths could be obtained by *C-T* equations.

Table 9 Structural damage degrees corresponding to different flight strengths

| Flight strength | Damage per year(Without protection coating) | | | |
|---|---|---|---|---|
| (baseline fh/year) | A | B | C | D |
| 200 | 0.1107 | 0.1205 | 0.1272 | 0.1403 |
| 150 | 0.0890 | 0.0985 | 0.1045 | 0.1170 |
| 100 | 0.0669 | 0.0753 | 0.0813 | 0.0931 |

Thus, the total damage of specimens could be calculated according to service progress.

A. The failure time of surface protection coating is 5years in area A, so the damage could be obtained by Eq. (11) in the first 5years based on MINER theory.

$$d_1 = \frac{100*5}{3421} = 0.1467 \tag{11}$$

B. The surface protection coating has failure when the aircraft service in area A at sixth year, so the damage could be obtained by Eq. (12) in the last 1year.

$$d_2 = 0.0669 \tag{12}$$

C. When the aircraft service 4years at flight strength of 100fh/year in area B, the damage could be obtained by Eq. (13).

$$d_3 = 0.0753 * 4 = 0.3012 \tag{13}$$

D. When the aircraft service 2years at flight strength of 200fh/year in area C, the damage could be obtained by Eq. (14).

$$d_4 = 0.1272 * 2 = 0.2544 \tag{14}$$

We assumed that the damage can be accumulated using Miner theory. So the residual life of the aircraft is shown as equation (15) and (16):

$$d_{re} = 1 - 0.1467 - 0.066 - 0.3012 - 0.2544 = 0.2317 \tag{15}$$

$$N_{re} = 0.2317 * 3421 = 789.6 \tag{16}$$

Thus, the total fatigue safe life was calculated by ALSE as shown in Eq. (17):

$$N_{pr} = 792 + 600 + 400 + 400 = 2192 \tag{17}$$

The error among fatigue test results without corrosion, test results of team (Ⅱ) and the prediction life of ALSE were shown in Table 10.

Table 10 The error between prediction life and test results

| Test results of team (Ⅱ) | Prediction life of ALSE | Fatigue safe life without corrosion |
|---|---|---|
| 2198 | 2192 | 3421 |
| Error of prediction life | 0.3% | 55.6% |

If we administered the service using fatigue test results without corrosion, the fatigue safe life is 3412 flight hours and it is larger than the test results of team (Ⅱ). So, the fatigue safe life is not really safe. While the prediction life of ALSE is smaller than the test results of team (Ⅱ), it is safe to use the life of aircraft completely.

## 6. Summary

A new prediction method named ALSE is presented and its development method is described. The ALSE building under alternate action corrosion and fatigue can well present the real service progress. If we could build the C-T curve in different service area got the service time and flight strength, we can predict the service safe fatigue life with a high precision and the potential service life of aircraft can be used plenarily.

## 7. Acknowledgements

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