Research on Fatigue Curves for Pre-corroded Aircraft Structures

WANG Zhong-bo, LIU Wen-ting, HE Xiao-fan

(*School of Aeronautic Science and Technology, Beijing University of Aeronautics and Astronautics, Beijing 100083, China*)

Abstract: To quantitatively evaluate the effects of corrosion during grounding on fatigue life of aircraft structures, a new power equation is proposed using two-variable linear regression method. That the slope is a constant and the logarithmic intercept is a linear function of pre-corrosion time makes this equation advantageous: it has a simple form, its parameters have unambiguous technical and geometrical meanings, and it facilitates engineering applications. Three-parameter equations after pre-corrosion are obtained from back-calculation of fatigue limits, which have been successfully used to predict safe life of aircraft structures in corrosive environment.

Key words: fatigue life; pre-corrosion; fatigue curve; regression analysis; life prediction; corrosion

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摘 要:为评估地面停放预腐蚀对飞机结构疲劳寿命的影响,采用二元线性回归方法建立了一种新的预腐蚀疲劳曲线幂函数表达式。该曲线的指数为常量而对数截距是预腐蚀时间的线性函数。这两个特性使得曲线形式简单,参数几何、工程含义明确,并易于工程应用。通过寿命反推建立了参数修正的三参数预腐蚀疲劳曲线,该曲线已成功用于飞机结构腐蚀条件下的疲劳寿命估算。

关键词:疲劳寿命; 预腐蚀; 疲劳曲线;回归分析; 寿命估算; 腐蚀

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Corrosion that occurs during grounding, referred to as pre-corrosion, in fatigue critical locations of an aircraft structure causes a reduction in fatigue life[1-4]. Much research has been conducted to quantitatively evaluate the effects of pre-corrosion and a number of equations have been proposed for the description of fatigue curves (also referred to as *S-N* curves) after pre-corrosion, which are called *t-S-N* curves where t is pre-corrosion time[5-11]. In this research, a new power equation is proposed based on these studies and the back-calculation of fatigue limits of three-parameter equations after pre-corrosion are presented for safe life prediction of aircraft structures suffering from pre-corrosion.

1 New Power Equation

1.1 Existing equations

The equations mentioned above can be divided into two types according to the ways in which the effects of pre-corrosion are considered.

(1) The life-modified equations[5-7] are generally written as

$$N(t) = C_N(t) \cdot N(0) = C_N(t) \cdot (C \cdot S^{-m}) \quad (1)$$

$$N(t) = C_N(t) \cdot N(0) = C_N(t) \cdot \left(\frac{cA}{S-c}\right)^{\frac{1}{\alpha}} \quad (2)$$

where $C_N(t)$ denotes the pre-corrosion factor, first defined by Liu[2] *et al* to represent fatigue behavior after pre-corrosion, to prevent it being confused with parameter C; parameters m, C, A, α and c are estimated from fatigue data obtained in laboratory air and at room temperature (hereafter in general environment).

(2) The general form of the parameter-modified equations[8-11] is

$$S^{m(t)} \cdot N(t) = C(t) \quad (3)$$

$$S = c_P(t)\left[1 + \frac{A_P(t)}{N_P^{\alpha_P(t)}(t)}\right] \quad (4)$$

where parameters $m(t)$, $C(t)$, $A_P(t)$, $\alpha_P(t)$

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and $c_P(t)$ are functions of pre-corrosion time; and P is the survival probability.

Equations estimated by Wang[8,9] *et al* are specific ones only corresponding to several given pre-corrosion time, and the power equation proposed by Yang[10] *et al* is not practical due to the complex relation $\lg C(t) \propto t^a$.

1.2 New equation

Fatigue tests of un-corroded and pre-corroded specimens with a central hole for wing skin are performed at two stress levels using a stress ratio of 0.06 in general environment[5]. Results are listed in Table 1.

Table 1 Fatigue test results after pre-corrosion

Pre-corrosion	$S_1 = 140.0$MPa			$S_2 = 100.0$MPa		
time/d	N/cycle	n	s	N/cycle	n	s
0	47 898	4	0.038 4	154 578	4	0.026 8
5	60 014	4	0.034 1	167 831	4	0.042 1
10	51 410	4	0.030 9	151 321	4	0.049 3
20	31 486	4	0.039 9	98 057	4	0.048 2
45	19 168	4	0.052 2	51 631	6	0.039 8

According to the characteristics of fatigue behavior after pre-corrosion for aircraft structures[2-4,6,11], two assumptions can be made: fatigue life after pre-corrosion of a given time fits a log normal distribution, *i.e.*, $\lg N(t)$-$N(\mu(t), \sigma^2(t))$; the standard deviation is a constant independent on stress level and pre-corrosion time, *i.e.*, $\sigma(t) = \sigma$.

Conducting two-variable linear regression yields

$$\lg N(t) = 11.64492 - 0.01121t - 3.20298\lg S \tag{5}$$

Regression results are listed in Table 2 and fitting curves are shown in Fig.1.

Table 2 Regression results

b_0	b_1	b_2	R^2	$\bar{R}^2$	F
11.64492	−0.01121	−3.20298	0.971	0.963	118.86
t_0	t_1	t_2	s	n	
21.49	9.33	12.27	0.060	10	

From Eq.(5) a new power equation describing t-S-N curves is obtained

$$S^{m_t} \cdot N(t) = 10^{a+bt} \tag{6}$$

1.3 Advantages of new equation

(1) From Eq.(6), it can be seen that the slope $m(t)$ degenerates into a constant m_t, and that the logarithmic intercept is linearly related to pre-corrosion time, *i.e.*, $\lg C(t) = a + bt$. The former characteristic can be called the constant slope, and the latter is named the log-linear intercept here.

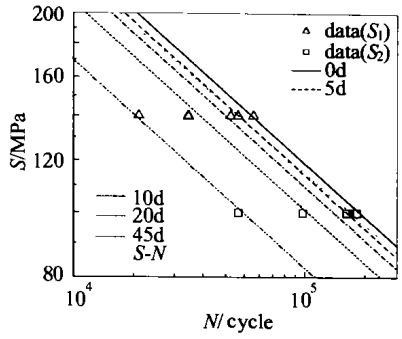

Fig.1 t-S-N curves and S-N curve

That $m_t = 3.202\,98$ and $C(0) = 10^{11.644\,92}$ are respectively approximate to $m_0 = 3.325\,8$ and $C_0 = 10^{11.852\,5}$ of the S-N curve obtained in general environment[5] indicates the feasibility of the new equation, which is shown in Fig.1.

(2) The geometrical meaning of the constant slope is clearly illustrated by the parallel straight lines in Fig.1. In addition, if a preliminary life prediction of an aircraft operating in weak corrosive environment is demanded, m_t may take m_0 value. Finally, this characteristic facilitates parameter estimate and helps reduce both corrosion and fatigue tests.

(3) The log-linear intercept shows that the log-life after pre-corrosion is a linear function of pre-corrosion time at a specific stress level as shown in Fig.2. If fatigue life after pre-corrosion of t is divided by that of 0, the single-parameter exponent

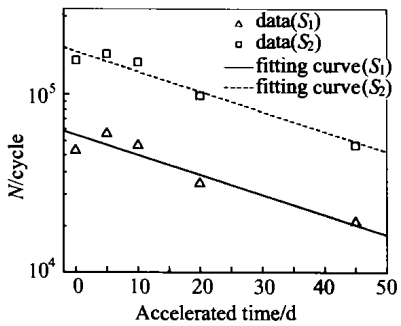

Fig.2 Fitting curves at $S_1 = 140.0$MPa and $S_2 = 100.0$MPa

equation of C-t curve can be obtained that is adopted by He[12] to demonstrate the generality of C-t curves

$$C_N(t) = \frac{N(t)}{N(0)} = \frac{10^{(a-m_t\cdot\lg S)+bt}}{10^{(a-m_t\cdot\lg S)}} = 10^{bt} \quad (7)$$

(4) According to the second assumption, the similar conclusions can be drawn for P-S-N curves after pre-corrosion, also called t-P-S-N curves.

2 Three-parameter Equation

Since establishing all the three relations between parameters $c_P(t)$, $A_P(t)$ and $\alpha_P(t)$ in Eq. (4) to pre-corrosion time t would be a prohibitive task in engineering, Eq.(4) is reduced to a simpler form

$$S = c_P(t)\left(1 + \frac{A_P}{N_P^{\alpha_P}}\right) \quad (8)$$

where A_P and α_P are shape parameters of the P-S-N curve estimated at a given stress ratio R^* in general environment[11]. Such a P-S-N curve, however, is usually unavailable in design phrase because structural fatigue tests are expensive and time consuming. To solve the problem, A_P and α_P are substituted by material constants or by the shape parameters for the corresponding fatigue critical location of its prototype or of a similar aircraft because these two locations have a approximate theoretical stress concentration factor, have similar design detail feature, are made of the same material and experienced the same process. Therefore, the third parameter $c_P(t)$ can be back-calculated as follows on the assumption that they have the same t-P-S-N curves[13].

Safe life of the prototype or of the similar aircraft after pre-corrosion of t time is calculated by

$$N_P(t) = N(t)/L_f = [N(0) - at^b]/L_f \quad (9)$$

where $N(0)$ is the mean life in general environment; a and b are constants determined by fatigue tests[3]; and L_f is life scatter factor, usually 4 – 6 for aircraft structures. Let $N_P(t)$ be the object life, we can determine $c_P(t)$ by any suitable method such as the bisection method. An following example shows the feasibility of this method.

The main beam of an aircraft currently in service is made of 30CrMnSiNi2A forging with I-shaped section. The fatigue critical location is one of the fastener holes of the lower flange for the beam with theoretical stress concentration factor $K_t = 2.35$. The values for shape parameters of material P-S-N curve with the same K_t at the stress ratio $R^* = 0.18$ are $A_P = 99.96$, $\alpha_P = 0.4702$. Safe life of its similar aircraft is determined by $N_P(t) = 1558 - 16.4525t^{0.6678}$. $c_P(t)$ for each year are back-calculated, then life prediction are carried out according to Miner's law. The predicted safe life corresponding to 100 flight hours per year in general environment is 2911 flight hours and in corrosion environment is 2731 flight hours neglecting the effects of corrosion during flight[2,4,6]. The ratio of the latter to the former, called fatigue life factor, is 0.904. Fatigue curves after pre-corrosion of 0, 10, 20, and 30 years are shown in Fig.3.

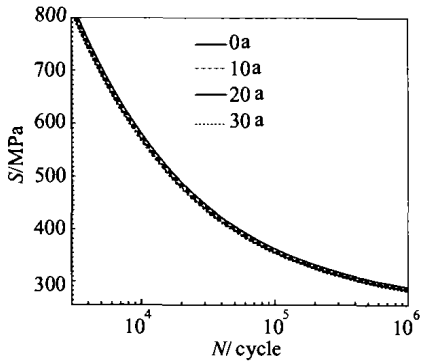

Fig.3 Fatigue curves for the main beam after pre-corrosion of 0, 10, 20 and 30 years

3 Conclusions

(1) The new power equation has two substantial characteristics: the constant slope and the log-linear intercept. These two characteristics lead to many advantages the new equation has a simple form; its parameters have unambiguous technical and geometric meanings; and it facilitates engineering applications.

(2) Three-parameter equations after pre-corrosion obtained from back-calculation of fatigue limits are practical for life prediction of aircraft structures operating in corrosive environment.

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Biographies:

WANG Zhong-bo Born in 1977, he received the B. S. degree in flight vehicle design and engineering at Beijing University of Aeronautics and Astronautics (BUAA) in 2000. Now he is a Ph. D. candidate in engineering mechanics. His research interests include fatigue analysis in corrosive environment and fatigue properties of Titanium alloy welding structures. Tel: (010) 82315738, E-mail: aerobo@163.com

LIU Wen-ting Born in 1940, Professor of BUAA. He was contributed to these areas: fatigue and fracture mechanics; structural durability and reliability; damage tolerance design; probabilistic fracture mechanics. Now he is interested in life estimation of aircraft structures in corrosive environment. Tel: (010)82315738, E-mail: lwtjiang@163.com

HE Xiao-fan Born in 1976, he received the B.S. degree at BUAA in 1998 and the Ph. D. degree in 2003. Now he is working as a Post-doctor in Station of Aeronautic & Astronautic Science and Technology. His research interests include structural life reliability under corrosive condition and structural durability. Tel: (010)82315738, E-mail: buaa-he@cert.org.cn