Fatigue Life Prediction Based on Walker and Masson Models

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ABSTRACT

It is known that mean stress has significant effects on fatigue life prediction, and various modifications have been developed to explain the mean stress effect, yet seldom accounting for mean stress sensitivity. The Smith-Watson-Topper (SWT) model is one of the most widely used models that can give satisfactory predictions, and it is viewed as a particular case of Walker model when the material parameter $\gamma = 0.5$. The Walker equation takes both the mean stress effect and sensitivity into account and can give accurate predictions in many fatigue programs. In this paper, based on the Walker model and Masson model, a modified model accounting for both the mean stress effect and the mean stress sensitivity is proposed to estimate the fatigue life. Three sets of experimental data are used to validate the applicability of the proposed model. A comparison between the SWT model and Morrow model is also made. The results show that the proposed model has more accurate predictions than the others.

Keywords: Fatigue Life; Mean Stress; Life Prediction; Walker Model; Masson Model

1. INTRODUCTION

Fatigue failure under cyclic loading is a process of crack initiation and crack propagation. It is also a result of damage accumulation or strength degradation. Fatigue life prediction provides an effective method to avoid major accidents and disasters before failure. The symmetric cycling loads with no mean stress are usually used in laboratory loading conditions, while such fatigue loads are rarely found in practical engineering. Various methods have been developed to predict fatigue life without considering the mean stress effect, but most of mechanical components or structures usually undergo non-symmetrical cyclic loading. Therefore, it is necessary to consider the mean stress effect for increased prediction accuracy of fatigue life. To date, many analytical methods have been proposed to describe the mean stress effect for metalilc materials (Ince & Glinka, 2011), such as Gerber model, Goodman model, Soderberg model, Morrow model, Walker model, and SWT model.

The mean stress effect is quite different for different materials even for the same working conditions, which depends on the mechanical properties of materials. The mean stress or sensitivity on the material evolution behaviors is critical for life prediction, and many models accounting for the mean stress effect or sensitivity are proposed to estimate the fatigue life. Lorenzo et al. (1984) introduced a new approach to predict the fatigue life under mean stress consideration. Nihei et al. (1986) developed several damage parameters to describe the mean stress on the materials of steels and aluminium alloys. Wehner et al. (1991) investigated the effects of mean stress on the cyclic deformation and fatigue life of the hardened carbon steel. Ince et al. (2011) proposed a modification of Morrow and SWT mean stress correction models to predict fatigue life. Nieslony et al. (2013) used constant stress ratio S-N curve approach to account for the mean stress effect on fatigue strength. Lv et al. (2016) proposed a strain-life model by incorporating the Walker parameter and SWT parameter, which considers the sensitivity to mean stress in materials. Zhu et al. (2016) introduced two mean stress correction factors into a new mean stress corrected strain energy model.

Dowling et al. (2004 and 2009) found that the Walker model has greater advantages than other models, wherein an adjustable parameter γ is used to fit different scenarios and form a single trend curve instead of a family of curves. The magnitude of γ is an adjustable constant associated with the material properties, providing a good correction and sensitivity of mean stress for most metallic materials. The parameter γ is obtained from the experiments or the similar material fatigue properties, such as yield strength, ultimate strength, and fracture limit. Because of the additional efforts to get the value of γ , the SWT model may be a good choice for practical engineering application.

Masson (1965) introduced the relationship between fatigue life and total strain, without distinguishing which part is elastic or plastic. The Masson model can correctly present the endurance limit strain and has a good background in engineering. Therefore, a practical method is developed to estimate the fatigue life accounting for the magnitude of γ based on the Masson Model. Several sets of experimental data are used to validate the proposed model.

2. CONSIDERATION OF MEAN STRESS

The stress-life ($S-N$) or strain-life ($\varepsilon-N$) curve is usually obtained from the experiments under symmetry cycling loading, where the mean stress equals 0. Since mean stress has significant effects on the fatigue evolution behavior, it should be taken into account in fatigue life prediction. The mean stress is usually presented as a function of stress amplitude versus mean stress plot according to Haigh, and that the load amplitude of the endurance limit decreases with the mean stress in a special cycle loading (Klubberg et al., 2011). The cycle loads of structures can be described in Table 1.

Table 1 Relationship of loads

Parameter	Equation
Stress ratio	$R=\sigma_{\min}/\sigma_{\max}$
Stress amplitude	$\sigma_a=(\sigma_{\max}-\sigma_{\min})/2=\sigma_{\max}(1-R)/2$
Mean stress	$\sigma_m=(\sigma_{\max}+\sigma_{\min})/2=\sigma_{\max}(1+R)/2$

The structural components in service are subjected to the loading histories with non-zero mean stress, but the situation is called completely reversed cycling for a particular loading spectrum where the mean stress $\sigma_m=0$ or the stress ratio $R=-1$.

The mean stress correction models on fatigue behaviors have been reported quite intensively by developing empirical formulations for different metallic materials, as shown in Table 2. According to these theories and models (Lv et al, 2016; Dowling et al, 2009; Strizak et al, 2003), it is found that the Gerber model cannot consider the effects of compressive stress or tensile stress, and in most cases, the compressive stress can increase the fatigue life but the tensile stress will decreases it; the Goodman model is extremely inaccurate; the Morrow model could not be used for aluminium alloys unless the real fracture strength is employed; the SWT model is more accurate than other models, and it is a particular case of Walker model when γ=0.5; the Walker model which has a material-dependent parameter allows to calibrate the relationship for various groups of materials with different cycle loads, and the value of γ for some materials can be determined in the China aeronautical materials handbook (2001).

Table 2 Modifications of mean stress

Researcher	Model
Gerber	$\frac{\sigma_a}{\sigma_{ar}}+(\frac{\sigma_m}{\sigma_u})^2=1$
Goodman	$\frac{\sigma_a}{\sigma_{ar}}+\frac{\sigma_m}{\sigma_u}=1$
Soderberg	$\frac{\sigma_a}{\sigma_{ar}}+\frac{\sigma_m}{\sigma_y}=1$
Morrow	$\frac{\sigma_a}{\sigma_{ar}}+\frac{\sigma_m}{\sigma_f}=1$
Walker	$\sigma_{ar}=\sigma_{\max}^{1-\gamma}\sigma_a^{\gamma}=\sigma_{\max}(\frac{1-R}{2})^{\gamma}=\sigma_a(\frac{2}{1-R})^{\gamma}$
SWT	$\sigma_{ar}=\sqrt{\sigma_{\max}\sigma_a}=\sigma_{\max}\sqrt{\frac{1-R}{2}}=\sigma_a\sqrt{\frac{2}{1-R}}$

Some conclusions of the presented mean stress effect models can be drawn as follows: (Niesłony & Böhm, 2013)

(1) Some models are proposed based on the monotonic tensile tests with constant material properties, such as Gerber, Goodman and Soderberg model. Those models provide simple modifications based on the static properties of the material that are easily to obtain. They only justify a part of the properties by using the static properties, such as fatigue limit. While it ignores the changes of the material properties (strength degradation, cyclic hardening, cyclic softening) in fatigue loads. The fatigue behavior and the mean stress sensitivity are not taken into account in those models.

(2) A few models can describe the real performance of materials, which use material-dependent parameters to fit different materials, such as Walker model and Kwofie (2001) model. Those models with material coefficient make fatigue life prediction more accurate and can describe the material performance. However, different materials have different performances, and there are some additional efforts need to determine the material-dependent parameters.

In addition, almost all of the models do not give a direct formula between the number of cycles to failure and sensitivities of the material. The mean stress sensitivity with various cyclic loads in the fatigue behavior can be observed or detected, but these models ignore the effects, and they only provide a simple modification based on the statistical data to assess the fatigue life. Therefore, the material property sensitivities with mean stress should be taken into account in the proposed model, it will lead to more reasonable results and the description of mean stress.

3. STRAIN-BASED METHODS OF LIFE PREDICTION

The purpose of fatigue life prediction is to establish an accurate model with good prediction performances (Zhu et al., 2010, 2012 & 2013; Colin et al., 2010; Burger & Lee, 2013; Arcari et al., 2009). Several criteria (Korsunsky et al., 2007; Schijve, 2001; Kwofie & Chandler, 2001) have been developed to predict the fatigue life, such as stress-based, strain-based, energy-based, and fracture mechanic approaches. Among them, the strain-based method is predominantly used to characterize the fatigue life.

Under high cycle fatigue (HCF) regime, the dominant factor leading to failure is elastic strain while the plastic strain is negligible. The stress-life relationship can be described by the Basquin's model, that is

$$\sigma_a = \sigma_f^{'}(2N_f)^b \tag{1}$$

According to the Hooke's law, the elastic strain can be written as

$$\frac{\Delta\varepsilon_e}{2} = \frac{\sigma_a}{E} = \frac{\sigma_f^{'}}{E}(2N_f)^b \tag{2}$$

where σ_a is the stress amplitude, $\sigma_f^{'}$ is the fatigue strength coefficient, b is the fatigue strength exponent, N_f is the number of cycles to failure, $\Delta\varepsilon_e$ is the elastic strain amplitude, and E is the elastic modulus.

Under low cycle fatigue (LCF) regime, the dominant factor is the plastic strain and the elastic strain can be ignored. The strain-life relationship can be written as

$$\frac{\Delta\varepsilon_p}{2} = \varepsilon_f^{'}(2N_f)^c \tag{3}$$

where $\Delta\varepsilon_p$ is the plastic strain amplitude, $\varepsilon_f^{'}$ is the fatigue ductility coefficient, and c is the fatigue ductility exponent.

In general, the structure components will produce both elastic and plastic strain under working conditions. The only difference is that the elastic strain can be recovered. The total strain contains both elastic and plastic strains, which can be expressed as

$$\varepsilon_a = \frac{\Delta\varepsilon}{2} = \frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2} = \frac{\sigma_f^{'}}{E}(2N_f)^b + \varepsilon_f^{'}(2N_f)^c \tag{4}$$

where ε_a is local strain amplitude.

The Eq. (4) is also called Manson-Coffin equation. It has some shortcomings when the components are subjected to the load spectrums with non-mean stress, and thus it may lead to inaccurate results when predicting the HCF life (Sendeckyj, 2001).

Morrow and Socie (1980) suggested that the mean stress has more impact in long life regions than that in short life regions. The Morrow model can consider the elastic strain correction, which is given as

$$\varepsilon_a == \frac{\sigma_f^{'} - \sigma_m}{E}(2N_f)^b + \varepsilon_f^{'}(2N_f)^c \tag{5}$$

The Manson-Coffin equation with SWT modification accounting for the non-mean stress condition can be expressed as

$$\varepsilon_a\sigma_{\max} = \frac{(\sigma_f^{'})^2}{E}(2N_f)^{2b} + \varepsilon_f^{'}\sigma_f^{'}(2N_f)^{b+c} \tag{6}$$

However, Masson (1965) also proposed a formulation to model the fatigue life and strain, as shown in Eq. (7). The theory hypotheses that there exists a strain around the endurance limit, whose fatigue life is essentially infinite.

$$N_f = A(\Delta\varepsilon - \Delta\varepsilon_c)^\alpha \tag{7}$$

where $\Delta\varepsilon_c$ is the endurance-limit strain, A and α are the material constants which can be expressed by ductility and ultimate strength, respectively. Although the physical definition of these parameters is not given, they can be determined by the experimental data for satisfying the Eq. (7). It is obvious that $\Delta\varepsilon_c$ can be ignored if the value of $\Delta\varepsilon$ is larger under LCF regime, and the Eq. (7) would coincide with the plastic strain in Eq. (3).

In general, some metals (such as aluminium and copper) are thought to have no endurance limit, but it could be testified according to the experimental data. The stress amplitude becomes lower to a critical value and the number of cycles becomes larger than 5×10^7, the fatigue life curve will trend to horizontal line. The stress amplitude becomes lower to a critical value and the number of cycles become larger than 5×10^9, the test specimen will not become failure. Furthermore, the endurance limit can be expressed as σ_∞ (endurance limit stress) or $\Delta\varepsilon_c$. If the cyclic loading amplitudes or strain values are lower than σ_∞ or $\Delta\varepsilon_c$, the fatigue life trends to be infinite.

The most widely used model to describe the fatigue life is the Basquin equation, but it ignores the influence of the endurance limit stress and it is difficult to satisfy the HCF. Weibull proposed a stress-life formula shown as

$$N_f = C_f(\sigma_a - \sigma_\infty)^\beta \tag{8}$$

where C_f and β are the material constants, the value of β is less than 0. Eq. (8) could not present the mean stress effect, and it only satisfies the fatigue life curve at a certain condition.

Eq. (7) and Eq. (8) can reflect the relationship between fatigue life and stress or strain, but the mean stress effect and sensitivity are not taken into account. The definition and how to obtain the value of the material are given in Eq. (9).

$$\begin{cases} A = \varepsilon_f^{\ 2} \\ \Delta\varepsilon_c = \dfrac{2\sigma_{-1}}{E} - \dfrac{\varepsilon_f}{10^{3.5}} \\ \alpha = -2 \end{cases} \tag{9}$$

There is an assumption in Eq. (9) that the fatigue ductility coefficient $\varepsilon_f^{'}$ is equal to the real fatigue ductility coefficient ε_f. In fact, the values of ε_f and $\varepsilon_f^{'}$ are not always equal, and there are some other problems for consideration (Zhao & Jiang, 2008; Wang, 2006).

4. PROPOSED MODEL

It is obvious that the Walker model is a popular used theory to modify the mean stress using the adjustable parameter γ. Hence, we use the Walker exponent γ to modify Eq. (6) by accounting for the mean stress, shown as

$$N_f = A_0 (\Delta\varepsilon_{eq} - \Delta\varepsilon_0)^{\alpha_0} \tag{10}$$

where $\Delta\varepsilon_{eq}$ is the equivalent strain, $\Delta\varepsilon_0$ is the equivalent strain limit, A_0 and α_0 are material constants.

The relation between strain and stress in elastic range can be expressed as

$$\Delta\varepsilon = \frac{\sigma}{E} \tag{11}$$

Similarly, the equivalent local strain $\Delta\varepsilon_{eq}$ can be expressed as (Jaske et al., 1973)

$$\Delta\varepsilon_{eq} = \frac{\sigma_{eq}}{E} = \frac{\sigma_{\max}^{1-\gamma}(2\sigma_a)^{\gamma}}{E} = (2\varepsilon_a)^{\gamma}(\frac{\sigma_{\max}}{E})^{1-\gamma} \tag{12}$$

Eq. (12) shows that the total strain satisfies the Hooke's law if the elastic strain is a dominant factor of fatigue failure. In order to take both elastic and plastic strain into account, a compensation factor λ is introduced into the Eq. (16), shown as

$$\Delta\varepsilon_{eq} = \lambda\frac{\sigma_{eq}}{E} = \lambda\frac{\sigma_{\max}^{1-\gamma}\sigma_a^{\ \gamma}}{E} = \lambda(\varepsilon_a)^{\gamma}(\frac{\sigma_{\max}}{E})^{1-\gamma}$$
$$\lambda = \begin{cases} 1, & \sigma_{\max} \le \sigma_0 \\ \sigma_{\max}/\sigma_0, & \sigma_{\max} > \sigma_0 \end{cases} \tag{13}$$

Thus, a new fatigue life model can be obtained as

$$N_f = A_0[\lambda(\varepsilon_a)^{\gamma}(\frac{\sigma_{\max}}{E})^{1-\gamma} - \Delta\varepsilon_0]^{\alpha_0} \tag{14}$$

In Eq. (14), the adjustable parameter γ is incorporated into the Masson model. It takes both the mean stress effect and sensitivity into account for improving the prediction accuracy of fatigue life.

5. RESULTS AND DISCUSSIONS

In this section, three groups of experimental data (Wehner & Fatemi, 1991; Shi et al., 2001; Zhao & Jiang, 2008; Wang, 2006) are used to verify the applicability of the proposed model. A comparison between the experimental data and predicted results using Morrow model, SWT model and the proposed model is also made. The material properties of nickle-base super alloy GH4133, aluminum alloy 7015-T651 and SAE 1045 steel of HRC 55 are shown in Table 3. By using Eqs.. (5), (6) and (14), the predicted results of GH4133, 7015-T651 and SAE 1045 are presented in Figures1-3, respectively.

According to Figures 1-3, the life prediction results of SWT model and proposed model agree well with the test data with a life factor ±2 , while the predictions of Morrow model show a large scatter. The Morrow model tends to overestimate the fatigue life, and the fatigue life estimated by SWT model and proposed model are conservative.

Table 3 Material property of three alloys

Material	Yield strength σ_0(MPa)	Ultimate strength σ_b(MPa)	Elastic modulus E(GPa)	Walker component γ
GH4133	745	1109	214	0.55
7015-T651	489	561	71.7	0.53
SAE 1045	1731	2165	205	0.43

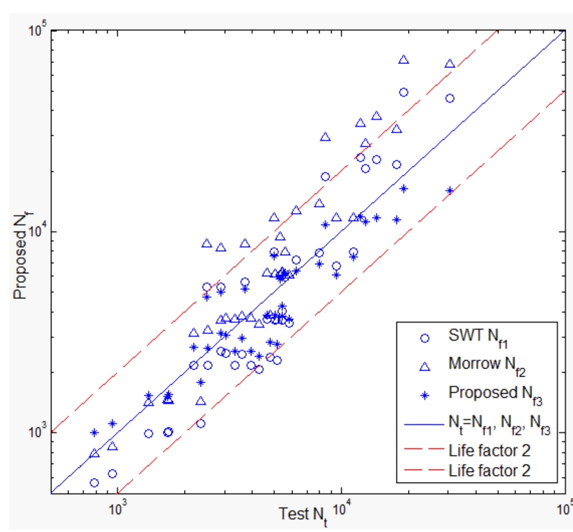

Figure 1. Predicted life N_f vs. the test data N_t of GH4133

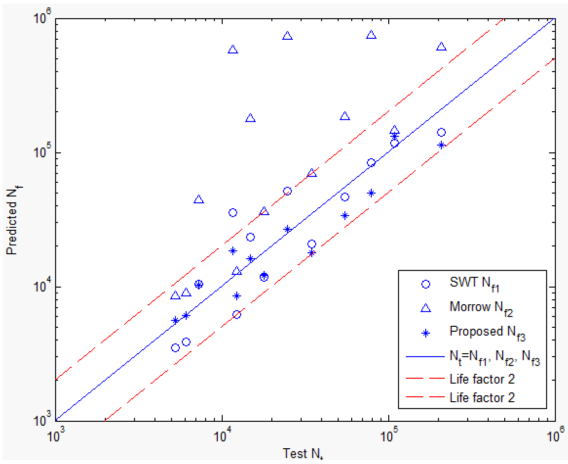

Figure 2. Predicted life N_f vs. the test data N_t of 7015-T651

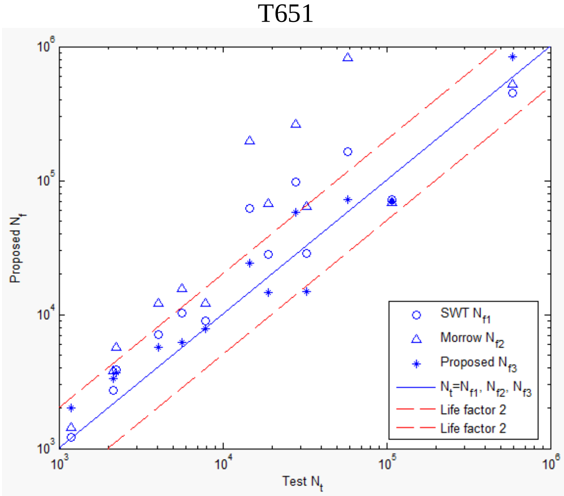

Figure 3. Predicted life N_f vs. the test data N_t of SAE 1045

In order to quantify the fatigue life prediction errors, the predicted life deviation is used to describe the accuracy between the logarithmic predicted life and logarithmic experimental life, as shown in Eq. (15). Then a standard deviation is calculated as the metric for different life prediction models, as shown in Eq. (16).. The standard deviation of fatigue life prediction by the chosen models is illustrated in Figure 4.

$$e = \log_{10}(N_f) - \log_{10}(N_t) \tag{15}$$

$$S_e = \sqrt{\frac{\sum_{i=1}^{n} e_i^2}{n}} \tag{16}$$

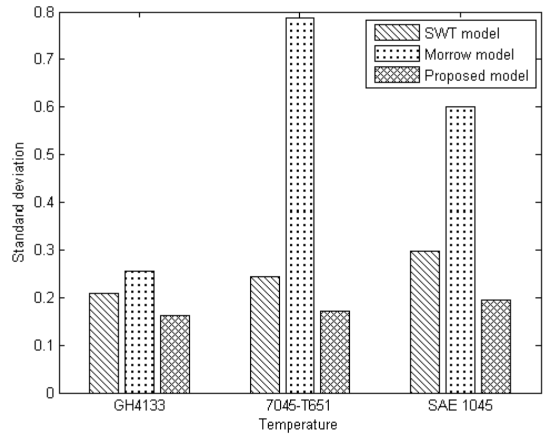

Figure 4. Standard deviation of fatigue life prediction

From Figure 4, the standard deviations of SWT model for three materials are less than 0.3, and the standard deviations of proposed model are less than 0.2. While for Morrow model with 7045-T651 and SAE 10, the standard deviations are relatively high. The predictability of SWT model is almost the same that of the proposed model. The reason may be attributed to that the γ values of three materials are very close to 0.5, but it should be noted that the predicted results of the proposed model become closer to the experimental observations than those of SWT model. Both the SWT model and the proposed method have a similar sensitivity parameter, which is not presented in the Walker equation as a result of larger prediction deviations. In contrast, the prediction accuracy using the proposed model is improved, and it is also suitable for LCF life prediction.

6. CONCLUSIONS

In this paper, a modified model accounting for both the mean stress effect and sensitivity is proposed to predict the fatigue life. Three groups of experimental data are used to validate the applicability and accuracy of the proposed model. Two widely used models are also employed for model comparison. According to the results obtained, some conclusions can be drawn as follows:

(1) The proposed model incorporates both the mean stress effect and sensitivity and predicts more accurate results than the SWT model and Morrow model.

(2) The material-dependent parameter γ can adjust several strain-life curves under different fatigue loadings to a single strain-life curve, and it also extends the life prediction range from LCF to HCF.

(3) The proposed model provides a total strain correction method to account for the mean stress effect and it still maintains a simple form.

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NOMENCLATURE

γ = Walker exponent

σ_a = stress amplitude

σ_m = mean stress

$\sigma_{\max}$ = maximum stress

$\sigma_{\min}$ = minimum stress

σ_f = fracture strength

σ_u = ultimate tensile strength

σ_y = yield strength

$\sigma_f^{'}$ = fatigue strength coefficient

σ_{ar} = equivalent fully reversed stress amplitude

σ_{∞} = endurance-limit stress amplitude

σ_{-1} = fatigue limit stress

$\Delta\sigma_{eq}$ = local equivalent stress

σ = applied load stress level

R = stress ratio

$\Delta\varepsilon_a$ = strain amplitude

$\Delta\varepsilon_e$ = elastic strain amplitude

$\Delta\varepsilon_p$ = plastic strain amplitude

$\Delta\varepsilon_c$ = endurance-limit strain

$\Delta\varepsilon_{eq}$ = local equivalent strain

$\Delta\varepsilon_0$ = equivalent endurance-limit strain

ε_f = real fatigue ductility coefficient

$\varepsilon_f^{'}$ = fatigue ductility coefficient

C_f = fatigue resistance coefficient

b = fatigue strength exponent

c = fatigue ductility exponent.

S_{eqv} = applied equivalent fatigue stress

$(S_{eqv})_c$ = equivalent fatigue limit

E = elastic modulus

N_f = predicted life

N_t = experimental life

λ = Compensation factor

A_0, α_0 = material constant

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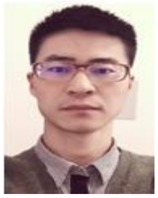

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