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A new non-linear continuum damage mechanics model for fatigue life prediction under variable loading

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Nomenclature

D - damage variable; σ_{Max} - maximum stress; σ_m - mean stress; $M(\ ), a(\ )$ - functions in the non-linear continuum damage model; M_0, a, b, β - coefficients of the non-linear continuum damage model; σ_{-1} - fatigue limit for fully reversed condition; $\sigma_l(\sigma_m)$ - fatigue limit for a non-zero mean stress; $\langle\ \rangle$ - defined as $\langle m\rangle = 0$ if $\langle m\rangle < 0$, $\langle m\rangle = m$ if $m>0$; σ_b - ultimate tensile strength; σ_y - yield strength.

1. Introduction

The mechanical components of major equipment including many operating in aviation, power generating, automotive industry and other industries are usually subjected to variable cyclic loading and fatigue. Therefore, fatigue is one of the main failure forms of these components. Fatigue failure is a damage accumulation process in which material property deteriorates continuously under fatigue loading and the damage depends on the size of stress and strain [1]. With the accumulation of fatigue damage, some accidents occur for these components. Research shows that a reliable lifetime prediction method is particularly important in the design, safety assessments, and optimization of engineering components and structures [2-5]. Thus, it is important to formulate an accurate method to evaluate the fatigue damage accumulation and effectively predict the fatigue life of these components.

Damage accumulation in materials is very important, but very challenging to characterize in a meaningful and reliable way. Until now, dozens of methods have been developed to predict the fatigue life. In general, fatigue damage accumulation theories can be classified into two categories: linear damage accumulation theories and non-linear damage accumulation theories. The linear damage rule (LDR), also called the Palmgreen-Miner rule (just Miner's rule for short) [6], is commonly used to calculate the cumulative fatigue damage based on the following assumptions [7]:

1. the rate of damage accumulation remains constant over each loading cycle;
2. fatigue damage occurs and accumulates only when the loading stress is higher than its fatigue limit;
3. the cycles be extracted and arranged in ascending order of magnitude without any regard for its order of occurrence.

According to these assumptions, fatigue life of components under variable amplitude loading can be estimated by:

$$D = \sum_{i=1}^{k} \frac{n_i}{N_i}, \tag{1}$$

where n_i is the number of loading cycles at a given stress level σ_i, N_i is the number of cycles to failure at σ_i, D is the total damage (it is usually assumed to be one at the point of fatigue failure life) as shown in Fig. 1.

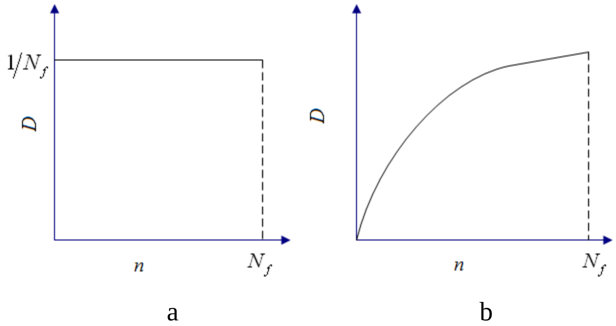
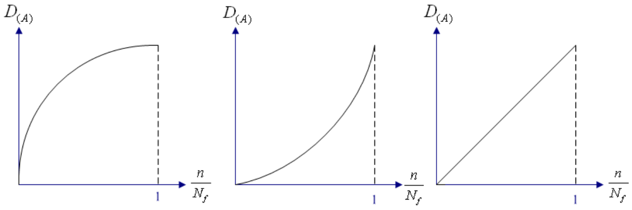


Fig. 1 Fatigue damage per loading cycle: a, the damage per loading cycle according to the Miner's rule; b, the relation between the cumulative damage and per loading cycle

However, Eq. (1) neglects the damage contribution of the loading stress which is lower than the fatigue limit. According to some experimental results such as: Lu and Zheng [8-10], Sinclair [11], and Makajima et al. [12], it has shown that the damage of low amplitude loads is one of the main reasons for prediction errors. Moreover, the influence of loading sequence effects on fatigue life is ignored in Miner's rule. That is to say, it is not sensitive to the loading sequence effects for the linear damage accumulation theory. Thus, Miner's rule often leads to a discrepancy of up an order of magnitude between the predicted and experimental life. According to the author's previous work [13], a new linear damage accumulation rule is put forward to consider the strengthening and damaging of low amplitude loads with different sequences using fuzzy sets theory. Consequently, Miner's rule has been undergone many modifications in an attempt to successfully apply this simple rule. And many researchers have tried to modify the Miner's rule, but due to its intrinsic deficiencies, no matter which version is used, life prediction based on this rule is often unsatisfactory [14].



a b c

Fig. 2 Different types of fatigue damage accumulation curves: a) the cumulative damage under high-low loading; b) the cumulative damage under low-high loading; c) the cumulative damage according to the linear damage rule

Accordingly, lots of non-linear damage accumulation methods have been proposed to consider the loading sequence effects, which can be depicted as shown in Fig. 2. In Fig. 2 the x-axis is the ratio of loading cycle and the y-axis is the cumulative damage. In Fig. 2, a is the cumulative damage under high-low and Fig. 2, b is that under low-high loading respectively. Fig. 2, c is the damage accumulation curve of Miner's rule. As is well known, a non-linear damage accumulation equation proposed by Marco and Starkey [1] is:

$$D = \sum_{i=1}^{k} \left(\frac{n_i}{N_i} \right)^{m_i} , \tag{2}$$

where m_i is a coefficient depends on the i-th level of load. It considers the effects of loading sequences. However, some research showed that only in some case for some materials, the fatigue lives predicted by Marco and Starkey's model shows a good agreement with the experimental results. In addition, it is difficult to determine the corresponding coefficient. Therefore, these equations have limited use in practical engineering application.

Recently, another approach, based on damage mechanics of continuous media, has been proposed since Kachanov presented the concepts of "continuum factor" and "effective stress" firstly [15]. This theory deals with the mechanical behavior of a deteriorating medium at the continuum scale. Chaboche and Lemaitre [16] applied these principles to formulate a non-linear damage evolution equation:

$$dD = f\left(\ldots\right) dN , \tag{3}$$

where the variables in the function f may be the stress, total strain, plastic strain, damage variable, temperature and/or hardening variables etc. In order to describe non-linear damage accumulation and loading sequence effects, in addition, the variables and the loading parameters in the function are inseparable. This model can calculate the damage provoked by the cycles below the fatigue limit and considers the effects of mean stress. Many forms of fatigue damage equation have been derived based on Chaboche's work [17-19].

In this paper, according to the varying characteristic of fatigue ductility, a modified non-linear uniaxial fatigue damage accumulation model is proposed on the basis of the continuum damage mechanics theory. And it can be used to predict failure of specimens and describe the whole process of fatigue damage accumulation.

2. Non-linear fatigue damage accumulation theory

For the fatigue problem, it should consider the following aspects [20]:

1. existing microinitiation and micropropagation;
2. nonlinear cumulative effects under two-stress level loading or multi-block loading;
3. existing fatigue limit which decreases after prior damage;
4. effects of mean stress on the fatigue limit or the S–N curve.

Based on the above mentioned characteristics of fatigue damage, for the uniaxial fatigue loading problems, the fatigue damage is defined, as originally proposed by Chaboche, by the following differential equation:

$$dD = D^{\alpha(\sigma_{Max},\sigma_m)} \left| \frac{\sigma_{Max} - \sigma_m}{M\left(\sigma_m\right)} \right|^{\beta} dN , \tag{4}$$

where the function α depends on the loading parameters (σ_{Max}, σ_m), and $\alpha(\sigma_{Max}, \sigma_m)$ is the function in the non-linear continuum damage model.

$$\left. \begin{aligned} & M\left(\sigma_m\right) = M_0\left(1 - b'\sigma_m\right); \\ & \alpha\left(\sigma_{Max}, \sigma_m\right) = a\left\langle \frac{\sigma_{Max} - \sigma_l\left(\sigma_m\right)}{\sigma_b - \sigma_m} \right\rangle; \\ & \sigma_l\left(\sigma_m\right) = \sigma_{-1}\left(1 - b\sigma_m\right) \end{aligned} \right\} \tag{5}$$

where M_0, a, b, b' and β are material constants. σ_{-1} is the fatigue limit under fully reversed condition, $\sigma_l(\sigma_m)$ is the fatigue limit under non-zero mean stress loading condition. Symbol $\langle\ \rangle$ is defined as $\langle m \rangle = 0$ if $m<0$, $\langle m \rangle = m$ if $m>0$.

Integrating Eq. (4) for constant σ_{Max} and σ_m, between D = 0 and D = 1 leads to:

$$N_F = \frac{1}{1-\alpha} \left[\frac{\sigma_{Max} - \sigma_m}{M\left(\sigma_m\right)} \right]^{-\beta} ; \tag{6}$$

$$D = \left(\frac{n_i}{N_F} \right)^{1/1-\alpha} . \tag{7}$$

This model can be extended from damage mechanics using the effective stress concept. And it assumes that damage does not exist before the half-life of materials, and the damage can only be measured at the last part of life, which cannot comprehensively reflect the fatigue damage mechanism [21]. Thus, it is important to define an adaptive fatigue damage variable which can establish a fatigue damage accumulation model and can comprehensively reflect the fatigue damage behaviour.

3. Establishment of a new non-linear fatigue damage accmulation model

Fatigue damage is a process of the micro-cracks and the micro-hole continually initiating and propagating due to the irreversible evolution of material microscopic structure. This irreversible evolution process directly affects the macro-property of materials. If the characteristic of fatigue ductility is combined with the continuum damage mechanics theory, we can rewrite Eq. (3) as follows:

$$dD = \frac{(1-D)^{\alpha(\sigma_{Max},\sigma_m)}}{\left[1-\alpha(\sigma_{Max},\sigma_m)\right]^2}\left|\frac{\sigma_{Max}-\sigma_m}{M(\sigma_m)}\right|^{\beta} dN\,. \qquad (8)$$

Integrating Eq. (8) from $D = 0$ to $D = 1$, the number of cycles to failure and the damage evolution equation expressed in a function of n_i/N_F can be obtained, respectively:

$$N_F = (1-\alpha)\left[\frac{\sigma_{\mathrm{Max}}-\sigma_m}{M(\sigma_m)}\right]^{-\beta}, \qquad (9)$$

$$D = 1-\left(1-\frac{n_i}{N_F}\right)^{1/(1-\alpha)}, \qquad (10)$$

where the exponent α depends on the loading function $\alpha(\sigma_{Max},\sigma_m) = 1-\dfrac{1}{a\,lg\left(\sigma_{Max}/\sigma_{-1}(\sigma_m)\right)}$, and σ_{Max} is the maximum stress.

If the loading parameters are the strains, the stress may be transformed to the strain by means of the cyclic stress–strain relationship:

$$\frac{\Delta\sigma}{2} = c\left(\frac{\Delta\varepsilon}{2}\right)^n, \qquad (11)$$

where c and n are the material constants, which can be obtained from uniaxial cyclic loading tests.

Therefore, Eqs. (8) and (9) can be rewritten as follows, respectively:

$$dD = \frac{(1-D)^{\alpha(\sigma_{Max},\sigma_m)}}{\left[1-\alpha(\sigma_{Max},\sigma_m)\right]^2}\left|\frac{c(\Delta\varepsilon/2)^n}{M(\sigma_m)}\right|^{\beta} dN\,; \qquad (12)$$

$$N_F = \frac{1}{a\,lg\left(c(\Delta\varepsilon/2)^n/\sigma_{-1}(\sigma_m)\right)}\left[\frac{c(\Delta\varepsilon/2)^n}{M(\sigma_m)}\right]^{-\beta}. \qquad (13)$$

For two-stress level loading, the specimen is firstly loaded at stress σ_1 for n_1 cycles and then at stress σ_2 for n_2 cycles up to failure. In order to make use of equivalence of damage for different loading conditions, it is possible to establish an equivalent number of cycles $n_2^{'}$ applied with stress amplitude σ_2 which would cause the same amount of damage as caused by n_1 cycles at σ_1:

$$1-\left(1-\frac{n_1}{N_{F1}}\right)^{1/(1-\alpha_1)} = 1-\left(\frac{n_2^{'}}{N_{F2}}\right)^{1/(1-\alpha_2)} \Rightarrow$$

$$\Rightarrow \frac{n_2^{'}}{N_{F2}} = \left(1-\frac{n_1}{N_{F1}}\right)^{(1-\alpha_2)/(1-\alpha_1)}. \qquad (14)$$

For the case of high-low loading sequence ($\sigma_1 > \sigma_2$), it follows:

$$\frac{1-\alpha_2}{1-\alpha_1} < 1;\ \frac{n_2}{N_{F2}} = 1-\left(\frac{n_1}{N_{F1}}\right)^{(1-\alpha_2)/(1-\alpha_1)} < 1-\frac{n_1}{N_{F1}}. \qquad (15)$$

Then fatigue cumulative damage under high-low loading sequence is as follows:

$$\frac{n_1}{N_{F1}}+\frac{n_2}{N_{F2}} < \frac{n_1}{N_{F1}}+1-\frac{n_1}{N_{F1}} = 1. \qquad (16)$$

For the high-low loading conditions, the cumulative damage is less than unit. In the same way, it may be proven, for the low-high loading conditions, the cumulative damage is more than unit. For the same two-level stress loading $\alpha_1 = \alpha_2$, then:

$$\frac{n_2}{N_{F2}} = 1-\frac{n_1}{N_{F1}} \Rightarrow \frac{n_1}{N_{F1}}+\frac{n_2}{N_{F2}} = 1. \qquad (17)$$

It is reduced to the Miner rule. Similarly, under multi-stress level loading condition and through sequential calculation, it is easy to get a fatigue damage cumulative formula using an auxiliary variable V:

$$V_{i-1} = 1-(1-D_{i-1})^{1-\alpha_i} \Rightarrow$$

$$\Rightarrow V_i = 1-(1-D_{i-1})^{1-\alpha_i}+\frac{n_i}{N_{Fi}} =$$

$$= 1-(1-V_{i-1})^{(1-\alpha_i)/(1-\alpha_{i-1})}+\frac{n_i}{N_{Fi}}\quad (i = 2,3,4,\ldots,n). \qquad (18)$$

The integration is pursued until $V_i = 1$, which corresponds to the fatigue life.

The proposed formulation for characterizing the damage evolution of metals is consistent with the physical significance of fatigue damage:

1. The damage variable is satisfied with the boundary conditions [22]:

$$n = 0,\ D = 0,\ n = N_F,\ D = 1; \qquad (19)$$

2. Fatigue damage is an irreversible process of material degradation and it increases monotonically with the applied cycles [23]:

$$\frac{\partial D}{\partial n} > 0\,; \tag{20}$$

3. The higher applied loading stress often leads to the larger fatigue damage:

$$\frac{\partial^2 D}{\partial n\, \partial \sigma} > 0\,. \tag{21}$$

4. Experimental verifications of the proposed model

The experimental data of the normalized 45 steel in [22] are used to verify the proposed model. For the normalized 45 steel, the mechanical properties are as follows: yield strength is $\sigma_y = 371.7$ MPa, ultimate tensile strength is $\sigma_b = 598.2$ MPa. The damage variable D is obtained by measuring the static relative ductility change of material. The comparison between the damage evolution curves and the experimental results are shown in Figs. 3 and 4, it should be noted that the results are satisfactory.

Since the life analysis under two-stress level loading is one of the basic random loading analysis, many fatigue damage accumulation models are based on the two-stress level loading experiments. Therefore, in order to verify the application of Eq. (16) under multi-stress level loading, two categories of experimental data of 30CrMnSiA [23] and 30NiCrMoV12 are used. The tests of 30CrMnSiA were performed by two groups. For the first group, the mean stress is 250 MPa and the maximum stress is 732-836 MPa. For the second group, the mean stress is 450 MPa and the maximum stress is 797-940 MPa. The results of 30CrMnSiA between experiment and prediction are listed in Table 1. Moreover, the experimental data of the 30NiCrMoV12 under two-stress level loading are used to verify the proposed model. The mechanical properties of 30NiCrMoV12 are as follows: yield strength $\sigma_y = 755$ MPa, ultimate tensile strength $\sigma_b = 1035$ MPa [24]. It is shown that in Figs. 5-7 the predicted results using the proposed model are satisfactory compared with the experimental results, which is better than Miner's rule.

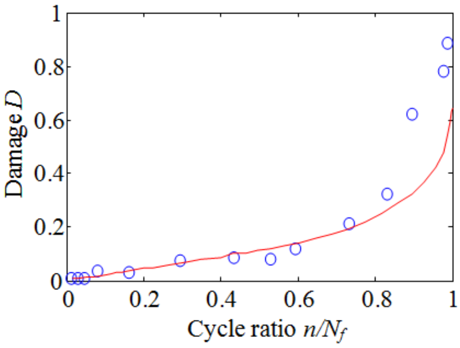


Fig. 3 Comparison between cumulative damage and cycle ratio for 45 steel under $\sigma_a = 405.8$ MPa

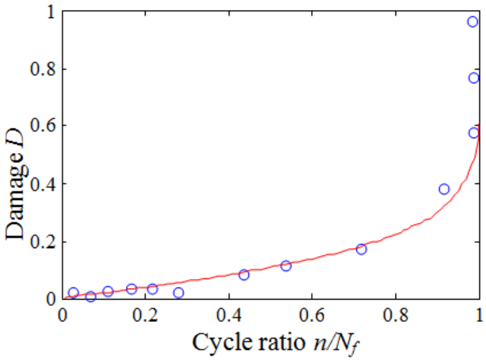


Fig. 4 Comparison between cumulative damage and cycle ratio for 45 steel under σ_a =330.9 MPa

Though the proposed model has the same basic principles as that of Chaboche and Lemaitre, it is easily applied, and the damage variable is directly related with the ductility which can be measured using a simple experimental procedure. In addition, it is verified using experimental data of three kinds of materials, and good results are obtained. However, the proposed model suits only for the fatigue life prediction of ductile material, and further

Table 1

Experiment and prediction comparison of two-stress level test results for 30CrMnSiA

Stress, MPa	Loading sequence	Cycles n_1	Cycle ratio $\frac{n_1}{N_{f1}}$	Experiment n_2	Experiment $\frac{n_2}{N_{f2}}$	Miner rule $\frac{n_2}{N_{f2}}$	Hashin's rule $\frac{n_2}{N_{f2}}$	Prediction $\frac{n_2}{N_{f2}}$
732-836	Low-high	13000	0.233	6602	0.917	0.767	0.954	0.888
	Low-high	15000	0.269	6501	0.903	0.731	0.938	0.863
	Low-high	25000	0.448	5400	0.750	0.552	0.817	0.756
	Low-high	35000	0.628	4428	0.615	0.372	0.627	0.628
	Low-high	45000	0.807	3254	0.425	0.193	0.365	0.460
	High-low	1200	0.167	36911	0.662	0.833	0.570	0.680
836-732	High-low	1800	0.208	32450	0.582	0.792	0524	0.610
	High-low	3000	0.417	16002	0.287	0.583	0.338	0.310
	High-low	5000	0.694	6969	0.125	0.306	0.158	0.085
797-940	Low-high	100000	0.288	3625	1.060	0.712	0.984	0.923
	Low-high	200000	0.576	2862	0.837	0.424	0.854	0.767
	High-low	1000	0.292	106320	0.306	0.708	0.297	0.327
940-797	High-low	1700	0.497	44821	0.129	0.503	0.182	0.108
	High-low	2400	0.702	22236	0.064	0.298	0.096	0.020
	High-low	3200	0.936	2432	0.007	0.064	0.011	0.001

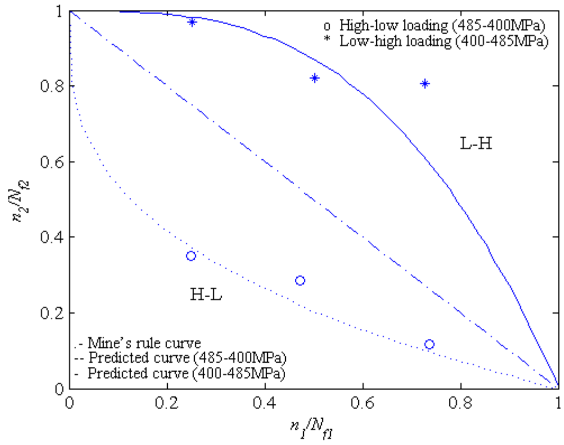


Fig. 5 Comparison between the experimental and predicted results for 30NiCrMoV12 (400-485 MPa)

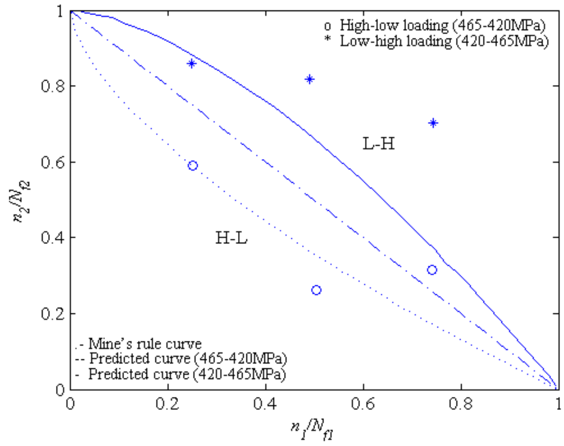


Fig. 6 Comparison between the experimental and predicted results for 30NiCrMoV12 (420-465 MPa)

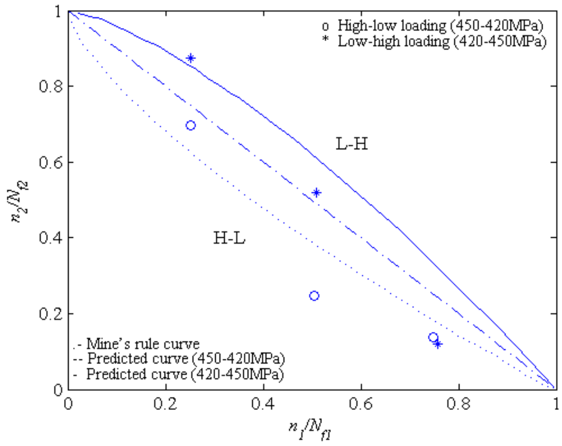


Fig. 7 Comparison between the experimental and predicted results for 30NiCrMoV12 (450-420 MPa)

validation on different materials are required. Moreover, application of the proposed method to full scale components under complex loading conditions, such as multi-axial fatigue loading, also needs further study.

5. Conclusions

By using the Chaboche's continuum damage theory as the starting point, a uniaxial non-linear fatigue damage accumulation model is proposed, which takes the effects of loading interaction and loading sequences into account. In addition, according to the equivalence of damage, the recurrence formula under multi-stress level loading is also derived, and the comparison between experimental data available from literature with predicted results showed a good agreement, which stated clearly that the proposed model has a reasonable descriptive ability of fatigue damage accumulation.

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NAUJAS NETIESINIO KOONTINIUMO PAŽEIDIMO MECHANINIS MODELIS NUOVARGIO TRUKMĖS PRIE KINTAMŲ APKROVŲ NUMATYMUI.

Reziumė

Nuovargis yra pažeidimo kaupimo procesas, kurio metu medžiagos savybės blogėja nepertraukiamai. Įprastiniam mechaninių komponentų irimo prie kintamų apkrovų pobūdžiui nuovargio laiko prognozavimo rezultatai yra labai svarbūs šių komponentų atrankai, projektavimui, ir saugumo įvertinimui. Pagrįstas kontiniumo irimo mechanikos teorija, šis straipsnis pateikia naują netiesinį irimo nuovargio kaupimo modelį nuovargio laiko esant kintamai apkrovai įvertinimui. Pasiūlytas modelis buvo suformuotas įvertinti medžiagos irimo raidą ir apkrovos seką nuovargio trukmei įvertinant skirtingas apkrovos sąlygas. Dar daugiau, jis nagrinėja pagrindinius įtempių reiškinius charakterizuojant medžiagos su keliais parametrais irimo raidą. 30NiCrMoV12 ir 30CrMnSiA eksperimento rezultatai prie dviejų įtempių apkrovų lygių pagal literatūros šaltinius buvo panaudoti pasiūlyto modelio patikrai. Prognozuojami nuovargio periodai panaudojant pasiūlytą modelį rodo gerą sutapimą su eksperimento rezultatais.

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A NEW NON-LINEAR CONTINUUM DAMAGE MECHANICS MODEL FOR THE FATIGUE LIFE PREDICTION UNDER VARIABLE LOADING

Summary

Fatigue is a damage accumulation process in which material property deteriorates continuously. For the usual failure mode of mechanical components under variable loading, fatigue life prediction issues are very important for selection, design, and safety assessments of these components. Based on continuum damage mechanics theory, this paper presents a new non-linear fatigue damage accumulation model for fatigue life prediction under variable loading. The proposed model has been formulated to take the damage evolution of material and the effects of loading sequence on fatigue life under different loading conditions into account. Moreover, it considers the mean stress effects through characterizing the damage evolution of materials with fewer parameters. Experimental data of 30NiCrMoV12 and 30CrMnSiA under two-stress level loading from literature were used to verify the proposed model. Predicted fatigue lives using the proposed model show a good agreement with the reported experimental data.

Keywords: non-linear fatigue damage accumulation, continuum damage mechanics, mean stress, loading sequence, fatigue life prediction.

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