THE CALCULATIONS IN A WHOLE PROCESS OF FATIGUE-DAMAGE-FRACTURE FOR COMPONENTS

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ABSTRACT

This paper has used a method to combine the local stress-strain with the local damage, studied some features and common grounds of material behaviors on each stage in a whole process of fatigue-damage-fracture, and suggested establishing the simplified double direction diagrams in a double direction coordinate system, that it can show involved some regularities on two directions, in order that the correlations among each equations and its each parameters of material behaviors on each stage can be shown illustratively, so that the many material parameters can be directly calculated from the regular constants of materials, and their physical and geometrical meanings can be also defined and connected with each other.

KEYWORDS

Combinatory coordinate system ; double direction diagrams; opposite direction equations.

INTRODUCTION

Many scientists have used lots of expensive experimental set-up, expended lots of times and moneys, investigated varied property material behaviors on each stage, provided various equations and material parameters. But up to now, the diagrams and equations in a whole process for systematically comprehensive describing material behavior are yet not of very much seeing. This paper has suggested establishing the double-direction diagrams in a double-direction coordinate system, which can illustratively show the features, common regularities and relationships among their curves equations and material parameters on each stage of material behaviors from uncrack to micro-crack initiation until fracture. Thereby the several material parameters can be direct made calculation from the typical constants of materials, the each equations and their parameters can be made connection and stating with each other on the geometry and physical meaning in a certain degree and in all its aspects.

A COMBINATORY TWO-DIRECTION COORDINATE SYSTEM AND TWO-DIRECTION DIAGRAMS

The figure 1 is a combinatory double logarithmic coordinate system shown with simplified two direction diagrams. It consists of four abscissa axes $O_1 1$, $O_2 2$, $O_3 3$, and $O_4 4$ and a double-direction ordinate axis $O_1 O_4$. Upward direction along the ordinate axis is presented as damage evolving rate dD/dN or crack propagation rate da/dN, and downward direction, presented as each stage life 2N from micro-crack initiation up to fracture, which are all described as damage evolving process of material behavior under symmetric cyclic loading. In double direction coordinate system, distance O_1O_2 between axis O_11 and O_22 is shown as region from uncrack to micro-crack initiation; distance O_2O_3 between axis O_22 and O_33, as region to be relative to life $N_{oi}^{min-mac}$ from micro-crack growth until macro-crack generation. Consequently, the O_1O_3 is as region relating to life N_o^{mac} from grains size to micro-crack initiation until macro-crack generation.

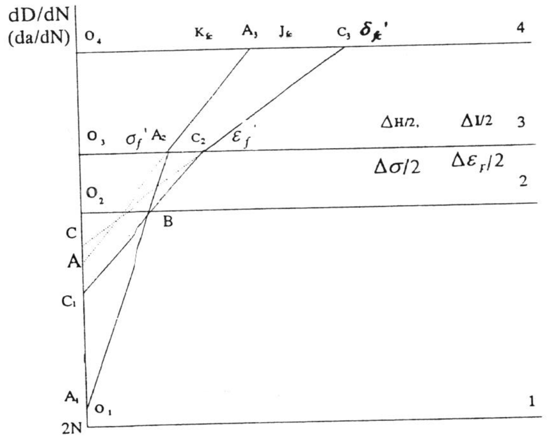

Figure 1. combinatory double direction coordinate system

The coordinate system combined from upward ordinate axis O_1O_4 and abscissa axes O_11, O_22 is presented to be relationship between damage evolving rate dD/dN and damage stress factor amplitude $\Delta H/2$ or between dD/dN and damage strain factor amplitude $\Delta I/2$ on crack generation stage; the coordinate system combined from O_1O_4 and O_33 (O_44) on same direction is presented to be the relationship between crack growth rate da/dN and stress intensity factor amplitude $\Delta K/2$, J-integral amplitude $\Delta J/2$, crack tip opening displacement amplitude $\Delta\delta_t$ /2 (da/dN-$\Delta K/2$, $\Delta J/2$, $\Delta\delta_t/2$) on crack growth stage. The coordinate system combined from downward ordinate axis O_4O_1 and abscissa axes O_11, O_22, O_33 is presented as the relationship between stress amplitude $\Delta\sigma/2$ and repeated number 2N or between plastic strain $\Delta\varepsilon_p/2$ and 2N. The curve A_1BA_2 shows the varying regularities of elastic material behaviors when it is under high cycle loading on macro-crack-forming stage: positive direction A_1BA_2 exhibits relation between dD/dN-$\Delta H/2$; negative A_2BA_1, between $\Delta\sigma/2$-2N. The point A_2 is a culminating one of curves A_1BA_2 and A_2A_3, between which varying of both slopes presents evolving regularity of stiffness drop at macro-crack forming and just starting steady propagation at this point A_2, and positive direction A_2A_3 presents the relation between da/dN-$\Delta K/2$; negative A_3A_2, between $\Delta K/2$-2N . The curve C_1BC_2 shows the varying regularities of plastic material behaviors, when it is under low-cycle loading on macro-crack forming stage: positive direction C_1BC_2 exhibits relation between dD/dN-$\Delta I/2$; negative C_2BC_1, between $\Delta\varepsilon_p/2$-2N. The point C_2 is a culminating one of curves C_1BC_2 and C_2C_3, between which varying of both slope exhibits evolving regularity of stiffness drop at forming macro-crack and just starting steady

propagation at this point C_2, and positive direction C_2C_3 exhibits relation the da/dN-$\Delta\delta_t/2$ ($\Delta J/2$); negative C_3C_2, between $\Delta\delta_t$ /2($\Delta J/2$)-2N.

In order to analyze and state problems in nature, the correlations among each material constants can be made to derive properly, so approximately assuming that: (1) The intersection point B of A_1A_2 and C_1C_2 in Fig.1 just is the critical one relative to threshold value ΔK_{th} at crack initiating. (2)The point A_2 is corresponding one for cycled stress amplitude $\Delta\sigma/2$ to arrive at the fatigue strength coefficient σ_f' that it also is a $\Delta\sigma/$ 2-value homologized to stress intensity factor amplitude $\Delta k/2$-value, when a macro-crack is forming under high-cycle loading; the point C_2 is corresponding one for cycled strain amplitude $\Delta\varepsilon_p/2$ to arrive at the fatigue ductility coefficient ε_f' that it also is a $\Delta\varepsilon_p$ /2-value homologized to crack opening displacement δ_t-value when a macro-crack is forming under low-cycle loading. But in the positive direction coordinate system, the abscissa axis O_33 existed for points A_2 and C_2 when the micro-cracks extend to macro-cracks forming and just starting steady propagation is as the delimiting line. (3) The points A_3 is the corresponded one when the $\Delta k/2$ or $\Delta J/2$-value arrives at K_{fc} or J_{fc} under high cycle and low or middle amplitude-value loading. The point C_3 is the corresponded one when the $\Delta\delta_t$ or Δ J-values arrive at $\delta_c(J_c)$-value under low cycle or high-amplitude-value loading. So, the abscissa axis O_44 when the loading arrives at the critical value and crack starts fast extending is a critical line.

CORRELATIONS AMONG EACH EQUATIONS AND THEIR MATERIAL PARAMETERS IN A WHOLE PROCESS OF FATIGUE-DAMAGE-FRACTURE UNDER HIGH-CYCLE LOADING

Under cyclic loading, due to the forming mechanisms of micro-crack and macro-crack are different, their behavior features on crack forming stage and crack growth stage are also different. Author recognized that in the crack forming stage, the damage evolving rate dD/dN (da/dN) of material fatigue-damage is proportional to damage parameter D or micro-crack size a. In other words, the relation between the dD/dN(da/dN)-D(a) has a good linear dependence. In this stage, the slope m_1-value of curve A_1BA_2 which shows elastic degree in material evolving process is larger and the gradient of A_1BA_2 becomes steep. But, after macro-crack forming, the da/dN shows obviously out varying regularity with the square root of the crack size ($\sqrt{a}$), and the slope m_2-value of the A_2A_3 becomes smaller than the m_1 of the A_1BA_2, the gradient is dropped. Consequently, on this two stages there are varied evolving equations.

Crack Forming Stage

In the dD/dN-$\Delta H/2$ of positive direction coordinate system, in the fatigue damage evolving process on crack forming stage, the material behavior evolves along positive direction of the A_1BA_2 that it should be described by following equation

$$dD/dN = A_1 \cdot \Delta H^{m_1} \quad \text{(Yu Yangui, 1992,1994a,1994b)} \tag{1}$$

where ΔH is called to be the damage stress factor range.

$$\Delta H = \Delta\sigma \cdot D^{\frac{1}{m_1}} \tag{2}$$

for eq.(2) instead of the ΔH in eq.(1), to obtain

$$dD/dN = A_1 \cdot \Delta\sigma^{m_1} \cdot D, \quad \text{(Yu Yangui,1993a)} \tag{3}$$

where $\Delta\sigma$ is a local stress range value. A_1 is a comprehensive property parameter of materiel which is a function value to bear a relation to fatigue strength coefficient σ_f', elastic exponent b'.

m_1 is a material constant. D is a damage parameter. When a material is loaded to the point B, its surface or interior grains of material commence damaging and forming micro-cracks. In the time, the grain size d* should be involved in micro-crack size a_o^{mic} as relating to baseline damage value D_o^{mic} to be equal to a_o/a^{mac}. And the a^{mac} is a macro-crack size, as a crack extends to the culminating point A_2 on the line A_1BA_2. It means that the macro-crack is forming, it is jest corresponding with the stress intensity factor range ΔK^{mac}-value at point A_2 , in the time, its relative damage value D^{mac} equals 1 ($D^{mac}=1$). In reality, the micro-yield appearance of some points in material has been occurred when the stress revel is obviously lower than the yield stress σ_y' . But the elastic strain component relative to this stress above mentioned which produces influence on damage is very small. Consequently the point B front a damage value D_o may be approximately expressed with an average size of grains ($D_o=d^*/a^{mac}$).

It is notable that the negative direction curve A_2BA_1 in the $\Delta\sigma/2$-2N (Fig. 1) is just described by the Basquin's equation (Li Ming, 1987, Michel et al., 1980)

$$\Delta\sigma/2=\sigma'_f(2N_f)^{b'}$$

or

$$\Delta\sigma^{-\frac{1}{b'}}N_f=C, \tag{4}$$

Reference (YuYangui,1992) indicates that the relations among the eq.(1),(3) and (4) can be derived between each other, and the material parameters obtained from them exist as following relations

$$m_1=-\frac{1}{b_1'} \tag{5}$$

$$A_1=2(2\sigma_f')^{-m_1}(\ln D^{mac}-\ln D_o), \qquad (MPa)^{-m_1}\%/cycle \tag{6}$$

$$C=\frac{1}{2}(2\sigma_f')^{-\frac{1}{b'}} \tag{7}$$

so

$$C=(\ln D^{mac}-\ln D_o)/A \tag{8}$$

and the relations between m_1 and b_1' are reciprocal ones. This can also see out from negative direction relation of the A_1BA_2 and A_2BA_1 on geometry. So that they are all agreement. Such, the A_1in eq.(1) (3) and the C in eq.(4) can be direct calculated from the typical constants σ_f',b_1' of material by means of the negative relations of the double direction curves and the negative direction equations.

Crack Propagation Stage

In the evolving process of material behavior on crack propagation stage, the relation between the da/dN-ΔK/2 in the positive direction coordinate system is to evolve along positive direction of the A_2A_3. It is well known that, as just had been described by the Paris's equation, i.e.

$$da/dN=A_2\Delta K^{m_2}, \qquad m/cycle \tag{9}$$

On the other hand, it could be also presented in the form of J-integral

$$da/dN=C_2(\Delta J_{eff})^{n_2}, \qquad m/cycle \text{ (Е.А.ГРИНЬ,1987)} \tag{10}$$

here, m_2 and n_2 are all material constants, also the slope of line A_2A_3. A_2 and C_2 are also

comprehensive parameters of material.

But, by the negative direction curve A_3A_2, their relationships are (Yu Yangui, 1991)

$$\frac{\Delta K}{2}=K'_{fc}(2N_{f_2})^{b_2'} \tag{11}$$

$$\frac{\Delta J_{eff}}{2}=J'_{fc}(2N_{f_2})^{c_2'} \tag{12}$$

in the eq.(11) and (12), K_{fc}' and J_{fc}' are respectively the critical value of stress intensity factor and J-integral under cyclic loading. Same, according to its opposite direction relationship between A_2A_3 and A_3A_2. It should also be derived out

$$m_2=-\frac{1}{b_2'} \tag{13}$$

$$n_2=-\frac{1}{c_2'} \tag{14}$$

$$A_2=2(2K_{fc}')^{-m_2}\frac{(a_c-a_o)}{(N_{f_2}-N_o)}, \qquad (MPa\sqrt{m})^{-m}m/cycle \tag{15}$$

$$C_2=2(2J_{fc}')^{-n_2'}\frac{(a_c-a_o)}{(N_{f_2}-N_o)}, \qquad (KN/m)^{-n}m/cycle \tag{16}$$

in the eq.(15) and (16), a_c is a crack critical size.

CORRELATIONS AMONG EACH EQUATIONS AND THEIR MATERIAL PARAMETERS IN A WHOLE PROCESS OF FATIGUE-DAMAGE-FRACTURE UNDER LOW-CYCLE

Under low-cycle loading, though the mechanism of material fatigue-damage-fracture is not complete same with High-cycle fatigue, micro-crack initiations of both are all caused for dislocation movements. It will be seen from this that the equations of quantitative calculating evolving process may be applied by same forming. But in which case, the dimension exhibited for loading amplitude value should be for $\Delta\varepsilon_p$ instead of $\Delta\sigma$ on the crack-forming stage, for $\Delta\delta_t$ instead of ΔK on the crack propagation stage.

Crack -Forming Stage

In the damage evolving process of present stage, the relation between the dD/dN-ΔI/2 in positive direction coordinate system should be evolved by positive direction of line C_1BC_2 , which it can be described in following equation

$$dD/dN=B_1\Delta I^{m_1'} \tag{17}$$

where ΔI is defined as the damage strain factor range,

$$\Delta I=\Delta\varepsilon_p\times D^{\frac{1}{m_1'}}, \tag{18}$$

obtained form for the eq.(18) instead of the ΔI in eq.(17) is

$$da/dN=B_1\Delta\varepsilon_p^{m_1'}D \tag{19}$$

Where the $\Delta\varepsilon_p$ is a local plastic strain range value. B_1 is also comprehensive property parameter. m_1 is a constant of plastic material, that it is presented as slope of the line C_1BC_2 . But the negative direction curve C_2BC_1 in opposite coordinate system $\Delta\varepsilon_p/2$-2N, that as is described by the Manson-Coffin equation, i.e.

$$\frac{\Delta\varepsilon_p}{2} = \varepsilon_f'(2N_{f_1})^{c_1'}$$

or

$$\Delta\varepsilon_p^{-\frac{1}{c_1'}} N_{f_1} = C^*, \tag{20}$$

According to opposite dependence between C_1BC_2 and C_2BC_1, then the eq.(19) and eq.(20) should be derived with each other, the relation between their parameters is that

$$m_1' = -\frac{1}{c_1'} \tag{21}$$

$$B_1 = 2(2\varepsilon_f')^{-m_1'}(\ln D^{mac} - \ln D_o), \tag{22}$$

$$C^* = \frac{1}{2}(2\varepsilon_f')^{-\frac{1}{c_1'}}$$

consequently

$$C^* = \frac{(\ln D^{mac} - \ln D_o)}{B_1} \tag{23}$$

As with case above mentioned , the m_1' and c_1' are also reciprocal dependence, this one with which the relationship between line C_1BC_2 and C_2BC_1 is opposite direction dependence on geometry is also agreement. So, the parameter B_1 and C^* could be direct calculated out from ε_f', C_1'.

Crack Propagation Stage

In the evolving process of material behavior on the present stage, the relation between the da/dN-$\Delta\delta_t$ in the positive direction coordinate system is to evolve along C_2C_3, and this simplified line was described by the crack opening displacement range $\Delta\delta_t$ in reference(В . В . П о к р о в с к и й ,1987)

$$da/dN = B_2(\Delta\delta_t)^{\lambda_2}, mm/cycle \tag{24}$$

author recognized that the B_2 is a comprehensive material parameter in connection with critical value δ_c and slope λ_2 of curve C_2C_3. Of course, this one may be exhibited by that J-integral forming (10).

However, by its negative direction curve C_3C_2, it should be

$$\frac{\Delta\delta_t}{2} = \delta_c 2(N_{f_2})^{c_2'} \tag{25}$$

According to the relation between C_2C_3 and C_3C_2, it should be derived out

$$\lambda_2 = -1/c_2' \tag{26}$$

$$B_2 = 2(2\delta_c)^{-\lambda_2}\frac{(a_c - a^{mac})}{(N_{f_2} - N^{mac})}, \qquad (mm)^{-\lambda_2}\cdot mm/cycle \tag{27}$$

DISCUSSIONS

The curves $A_1BA_2A_3$ and $C_1BC_2C_3$ in Fig.1 are evolving ones of material behaviors in a whole process, which are respectively corresponding to high-cycle fatigue and low-cycle fatigue, also corresponding to evolving behaviors of the elastic material and the plastic material .In reality the properties of various material are all to have some divergence . This paper only carries out approximately to analyze and investigate with respect to general regularities.

In Regard to Analysis and Explanation for Several Straight and Their Culminating Points.

On the macro-crack forming stage, assuming that the intersection point B between the high cycle fatigue curve A_1BA_2 and the low-cycle fatigue curve C_1BC_2 is corresponding to σ_y' (Michel, 1980). For elastic-plastic material, it would occurs to yield and damage in varied degree at point B, and it would evolves along line BC_2 , its slope is become from m_1=-1/b_1 of A_1BA_2 to m_1'=-1/C_1 of BC_2. This means that for this material, its stiffness would be decreased, and its damage value increased in varied degree from point B starting.

On crack propagation stage, the BA_2A_3 and BC_2C_3 are respectively as varied crack growth curves of two type of material or two categories of fatigue, in which, the BA_2 and BC_2 are as small crack growth stage , A_2A_3 and C_2C_3 , as macro-crack growth, points A_2 and C_2 are the culminating points as macro-crack starting steady growth up to critical point B 3, C_3. The slopes of their curves are also occurred to change at points B_2 and C_2 from m_1=-1/b_1' of BA_2 to m_2=-1/b_2' of A_2A_3 , from λ_1'=-1/C_1' of $BC_2$to m_2'=-1/C_2' of C_2C_3, that as just state obvious drop of their stiffness on this stage.

By the way, if the region between O_11 and O_22 is divided as from uncrack, micro-crack initiation to small crack forming stage; between O_22-O_33, as from small crack growth to macro-crack forming stage; between O_33-O_44, as from macro-crack growth to fracture stage. Then, a whole process of material behavior may be also divided to be three stages, for which it can be also illustratively shown out in Fig.1.

In Regard to Relationship Between The Damage Evolving Law and The Miner's Rule.

It should be indicated that the evolving process of positive and negative direction curves in Fig.1, which as is illustrative expression of the Miner's Rule of cumulative damage in double direction system. The equations (1),(3) and (17),(19) just describe directly to them . They can be all used to estimate the whole process life by derived two stages in reference (Yu Yangui, et al., 1994c).

6. CONCLUSIONS

1. The paper has used a method to combine the local stress-strain with the local damage, suggested establishing simplified double direction curves in a double direction coordinate system, as a consequence, the each equations and their material parameters with relative dependence can be qualitatively made derivation from each other.

2. A double coordinate system and its double direction curves can also illustratively exhibit positive-negative relation between each concerned curves, so their material parameters can be directly calculated from the regular constants of material, and their physical and geometrical meanings can be also defined and connected with each other .

3. The correlations among various equations and parameters have be induced in following table (Yu Yangui, 1993b).

Table 1 Correlations among each equations and its each parameters

crack forming stage				
Type of fatigue	high-cycle		low-cycle	
direction of curves	positive	negative	positive	negative
name of curve	A_1BA_2	A_2BA_1	C_1BC_2	C_2BC_1
equations	$\frac{dD}{dN} = A_1 \Delta H^{m_1}$ $\frac{dD}{dN} = A_1 \Delta \sigma^{m_1} D$	$\frac{\Delta\sigma}{2} = \sigma_f'(2N_{f_1})^{b_1'}$ $\Delta\sigma^{-\frac{1}{b_1'}} \cdot N_{f_1} = C$	$\frac{dD}{dN} = B_1 \Delta I^{m_1'}$ $\frac{dD}{dN} = B_1 \Delta \varepsilon_p^{m_1'} D$	$\frac{\Delta\varepsilon_p}{2} = \varepsilon_f'(2N_{f_1})^{c_1'}$ $\Delta\varepsilon_p^{-\frac{1}{c_1'}} \cdot N_{f_1} = C^*$
correlations among each parameters	$m_1 = -1/b_1'$ $A_1 = 2(2\sigma_f')^{-m_1}(\ln D^{mac} - \ln D_o)$ $C = \frac{1}{2}(2\sigma_f')^{-\frac{1}{b_1'}}$ $C = (\ln D^{mac} - \ln D_o)/A_1$		$m_1' = -1/c_1'$ $B_1 = 2(2\varepsilon_f')^{-m_1'}(\ln D^{mac} - \ln D_o)$ $C^* = \frac{1}{2}(2\varepsilon_f')^{-\frac{1}{c_1'}}$ $C^* = (\ln D^{mac} - \ln D_o)/B_1$	
geometry meaning of m_1 or m_1'	$m_1 = -1/b_1'$, It's slope of A_1BA_2 or A_2BA_1, $m_1' = -1/c_1'$ -- slope of C_1BC_2 or C_2BC_1			
physical meaning of m_1 or m'_1	They show elastic-plastic degree of material on first stage			
geometry meaning A_1 and B_1	$\lg A_1$ -- distance O_3A_1 on axis O_1O_4 for A_1BA_2 or A_2BA_1		$\lg B_1$ -- distance O_3C_1 on axis O_1O_4 for C_1BC_2 or C_2BC_1	
physical meaning of A_1 and B_1.	They are the comprehensive resistance of fatigue damage in connection with σ_f', m, (b_1') or ε_f', m',(c_1')			

crack propagation stage				
type of fatigue	high-cycle		low-cycle	
direction of curve	positive	negative	positive	negative
name of curve	A_2A_3	A_3A_2	C_2C_3	C_3C_2
equations	$da/dN = A_2 \Delta K^{m_2}$ $da/dN = C_2 \Delta J_{eff}^{n_2}$	$\frac{\Delta K}{2} = K_{fc}'(2N_{f_2})^{b_2'}$ $\frac{\Delta J}{2} = J_{fc}'(2N_{f_2})^{b_2''}$	$da/dN = B_2 \Delta\delta_t^{\lambda_2}$ $da/dN = C_2' \Delta J^{n_2'}$	$\frac{\Delta\delta_t}{2} = \delta_{fc}'(2N_c)^{c_2'}$ $\frac{\Delta J}{2} = J_{fc}'(2N_{f_2})^{c_2''}$

correlations among each parameters	$m_2 = -1/b_2'$ $A_2 = 2(2K_{fc}')^{-m_2}(a_c - a^{mac})/(N_{f_2} - N^{mac})$ $n_2 = -1/b_2''$ $C_2 = 2(2J_{fc})^{-n_2}(a_c - a^{mac})/(N_{f_2} - N^{mac})$	$\lambda_2 = -1/c_2'$ $B_2 = 2(2\delta_{fc}')^{-\lambda_2}(a_c - a^{mac})/(N_{f_2} - N^{mac})$ $n_2' = -1/c_2''$ $C_2' = 2(2J_{fc}')^{-n_2'}(a_c - a^{mac})/(N_{f_2} - N^{mac})$
geometry meaning	$m_2 = -1/b_2$ —slope of A_2A_3 or A_3A_2	$\lambda_2 = -1/c_2'$ --slope of C_2C_3 or C_3C_2
physical meaning	They show elastic-plastic degree of material on second stage	
geometry meaning	$\lg A_2$ --distance O_3O_4 on axis O_1O_4 for A_2A_3	$\lg B_2$ --distance O_3O_4 on axis O_1O_4 for C_2C_3
pysical meaning	They are comprehensive resistance of crack in connection with K_{fc}' (δ_c, J_c), m_2(λ_2,n_2)	

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