Damage Calculations in Whole Evolving Process Actualized for the Materials Behaviors of Structure with Cracks to Use Software Technique

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Abstract

To use the bidirectional combined coordinate system, depict their damage evolving behaviors for some steels, show their intersectional and complicated correlations : between the positive and negative direction, the positive and negative sign, the reciprocal relations and the symmetrical and unsymmetrical cycle relations in the coordinate system for their equations, curves, variables, material constants; design the calculation programs in whole process, which include the calculations of strength, of the damage evolving rate, of crack growth rate and their relative life at the crack forming and growth stage etc. thereby accomplish so as to connect among each branch disciplines on the modern mechanics. And also design a lot of the calculation programs and databases for the typical parts such structures with some crankshaft, cylinder block and connecting bar under multilevel complex loading etc. Predict it would be accepted and applied well in the engineering domain, for the economizing fatigue-damage-fracture testing bankroll, also have practical significance.

Keywords: Fatigue; crack; combined coordinate; whole process; calculation; software.

Nomenclature

1. Damage parameter: D =Damage variable of local damage in whole process, D_1 = Damage variable at the crack forming stage, D_2 = Damage variable at the crack growth stage.
2. Crack sizes: a_1 = Small crack size at the crack forming stage (variable), a_2 = Macro-crack size at the crack growth stage (variable), a_{mic} = Small-, micro-crack size (Ordaining value), a_{mac} = macro-crack size (Ordaining value), a_c = Critical size of macro-crack.
3. Stress and strain: ΔS = Nominal stress range, $\Delta\sigma_0$ = Remote stress range, $\Delta\sigma_e/2$ = Local elastic stress amplitude, $\Delta\sigma_p/2$ = Local plastic strain amplitude, σ_m = Localized mean stress.

4. Damage stress and strain factor: $\Delta H/2$ = Damage stress factor amplitude relative to small crack a_1, $\Delta I/2$ = Damage strain factor amplitude relative to small crack a_1.
5. Material constants at the crack forming stage: $b_1^{'}$ = Fatigue strength exponent in damage evolving under high cycle, $c_1^{'}$ = Fatigue ductility exponent in damage evolving under low cycle; m_1 = Fatigue strength exponent in small crack growth rate equation under high cycle, $m_1 = -1/b_1^{'}$; $m_1^{'}$ = Fatigue ductility exponent in small crack growth rate equation under low cycle, $m_1^{'} = -1/c_1^{'}$; $b_2^{'}$ = Fatigue strength exponent of the macro-crack growth stage under high cycle, $c_2^{'}$ = The fatigue ductility exponent at the macro-crack growth stage under low cycle; m_2 =The fatigue strength exponent in crack growth rate equation under high cycle, $m_2 = -1/b_2^{'}$; $m_2^{'}$ =The fatigue ductility exponent in crack growth rate equation under low cycle, $m_2^{'} = -1/c_2^{'}$.
6. Damage evolving rate: dD/dN = Damage evolving rate, dD_1/dN_1 =Damage evolving rate at the crack forming stage, dD_2/dN_2 =Damage evolving rate at the macro-crack growth stage; da/dN = Crack growth rate, da_1/dN_1 =Small crack growth rate at the crack forming stage, da_2/dN_2 = its rate at the macro-crack growth stage.
7. Life: N_{0i} =Life of corresponding to medial damage variable D_{0i} or medial small crack size a_{0i}.
8. Stress intensity factor, J -integral and Crack tip opening displacement: K_m = mean stress intensity factor, $\Delta K/2$ =Stress intensity factor amplitude of corresponding to macro-crack a_2;
$\Delta J/2 = J$ -integral amplitude corresponding to macro-crack a_2; $\Delta\delta_t/2$ = Crack tip opening displacement amplitude corresponding to macro-crack a_2.
9. Material constants at macro-crack growth stage: K_{1c} = Critical stress intensity factor corresponding to macro-crack a_c ; J_{1c} =Critical J -integral value corresponding to macro-crack a_c ; δ_c = Critical value of crack tip opening displacement corresponding to macro-crack a_c.

1. Introduction

In the modern scientific-technical and engineering domains, there are large numbers of microstructures and large-scale structures, and in all structures they can all come down to both subjects about the strength and the life. And designs and calculations of these structures are invariably applied with modern the fatigue-, damage and fracture mechanics discipline.
In the solid mechanics of modern times, sometimes people are studied in domain as the damage-mechanics or micro-fracture-mechanics for the damage of crystal

grain slippage, micro-bore, -hole, -crack and flaw size for □ 10^{-5} m; and are studied in domain as the macro-fracture mechanics for the damage of those bore, hole, macro-crack and flaw size for 10^{-4} to 10^{-3} m. Come to light, under fatigue loading the structures experience generally several stages from un-crack to fracture. And it is called to be the crack forming stage from un-crack to micro-crock initiation, growth to forming. At this stage, some new damage variable D_1, a_1 and its curves and equations are used to the damage calculations and the life estimations for a structure or material. And it is called to be the crack growth stage from macro-crack forming to steady going growth until to the celerity fracture. At this stage, another new variable D_2, a_2 and its curves and equations are also used to calculation and analysis to the intensity and life for a structure or material.

If design a mass of programs to analyze their intersectional relations in whole process on fatigue-damage-fracture of materials, to find out some alike or different law of material behavior at each stage, to find some correlations each other, to make these calculating variable D_1 and D_2, a_1 and a_2 and their curves, pictures and equations can be all connected one with another on physical and geometrical meaning and under certain condition can be also converted each other, accordingly form a comprehensive and profound cognition for diversified varying laws of material behaviors in whole process. Then to design a big programs consist of a lot of calculation ones and database about data, curves, picture and equations, thereby calculate and analyze the damage evolving rates, micro-crack growth rates and macro-crack growth rates and their corresponding life at each stage. Thus it would be accepted and applied widely in engineering domains for each new branch discipline on fatigue-damage-fracture, and also have practical significance for design and calculation of strength and life for structures.

2. Basic consider to connect intersectional correlations of calculation program among each branch disciplines on fatigue-damage-fracture

In the three of branch disciplines on fatigue-damage-fracture, for finding their correlations among material constants, curves, pictures and equations describing material behaviors at each stage, for connecting their relations each other, must put up analysises and developments for above mentioned parameters. It should explain here must be the local calculations for discussed problems at the crack forming and crack growth stage. Here it is by means of bidirectional combined coordinate system that adopting as figure 1 [1,2] express the damage evolving process of material behavior at each stage and in whole course, which is to consists of five abscissa axes OI’, O_1I, O_2□, O_3□, O_4IV and two bidirectional ordinate axis O_1 O_4 and $O_1^{'}$ $O_4^{'}$. Between the axes OI’and O_1I, it is calculation domain of the material mechanics; Between the axes O_1 I and O_2 II, it is calculation domain of the micro-fracture mechanics; Between the axes O_3III and O_4IV, it is calculation domain of the macro-fracture mechanics; Between the axes

O_2 II and O_3 III, it is all applicable calculation domain for the micro-fracture mechanics and macro-fracture mechanics. Upward direction along the ordinate axis is presented as damage evolving rate dD/dN or crack growth rate da/dN (that it can also carve up the damage evolving rate dD_1/dN_1 or small crack growth rate da_1/dN_1 at crack forming stage or the damage evolving rate dD_2/dN_2 or macro-crack growth rate da_2/dN_2 at crack growth stage), and downward direction, presented as each stage life 2N [1,2,3]. The distance OO_1 between axis OI' and O_1I is shown as region the nominal stress S or remote stress σ_o; The distance O_1O_2 between axis O_1I and O_2 □ is shown as region from un-crack to micro-crack initiation; distance O_2O_3 between axes O_2 □and O_3 □, as region relative to life $N_{oi}^{mic-mac}$ from micro-crack growth to macro-crack forming. Consequently, the O_1O_3 is as region relating to life N_{mac} from grains size to micro-crack initiation until macro-crack forming; the O_1O_4 is as region relating to the lifelong life N from micro-crack initiation until fracture of structure material. The coordinate system combined from upward axis O_1O_4 and abscissa axes O_1 I, O_2 □ is presented to be relationship between the damage evolving rate dD_1/dN_1 (or the small crack growth rate da_1/dN_1) and the damage stress factor amplitude $\Delta H/2$ (or damage strain factor amplitude $\Delta I/2$) at crack forming stage; the coordinate system combined from O_1O_4 and O_3 □ (O_4 IV) at same direction is presented to be the relationship between macro-crack growth rate and stress intensity factor amplitude $\Delta K/2$, J-integral amplitude $\Delta J/2$, crack tip displacement amplitude $\Delta\delta_t/2$ (da_2/dN_2 - $\Delta K/2$, $\Delta J/2$, $\Delta\delta_t/2$) at macro-crack growth stage. The coordinate system combined from downward ordinate axis O_4O_1 and abscissa axes O_1I, O_2 □, O_3 □ is presented as the relationship between the $\Delta H/2$-, $\Delta K/2$-amplitude and the life 2N (or between the $\Delta\varepsilon_p/2$-, $\Delta\delta_t/2$- amplitude and the life 2N). The curve abc is the nominal stress-strain calculation one; other curves are all calculation ones of the local problems. The ABA_1 shows the varying regularities of elastic material behaviors as under high cycle loading at macro-crack-forming stage: positive direction ABA_1 shows the relation between dD_1/dN_1 (or dq_1/dN_1)- $\Delta H/2$; inverted A_1BA, between the $\Delta H/2-2N$. The curve CBC_1 shows the varying regularities of plastic material behaviors, as is under low-cycle loading at macro-crack forming stage: positive direction CBC_1 shows the relation between dq_1/dN_1- $\Delta I/2$; inverted C_1BC, between the $\Delta\varepsilon_p/2-2N$. And the curve A_1A_2 shows as under high cycle loading at crack growth stage: positive direction A_1A_2, shows da_2/dN_2 - $\Delta K/2$ ($\Delta J/2$); inverted A_2A_1, shows between the $\Delta K/2$, $\Delta J/2-2N$. The C_1C_2 shows the positive direction relation between the da_2/dN_2 - $\Delta\delta_t/2$ under low-cycle loading, inverted C_2C_1, between $\Delta\delta_t/2$ ($\Delta J/2$)-2N. And it should point that the AA_1A_2 (curve 11') is expressed for the curve under symmetrical cycle loading (i.e.under zero mean stress); the DD_1D_2 (curve 33') for the curve under unsymmetrical cycle loading (i.e.under non-zero mean stress).

3. Main equations, material constants and their correlations each other in calculation programs

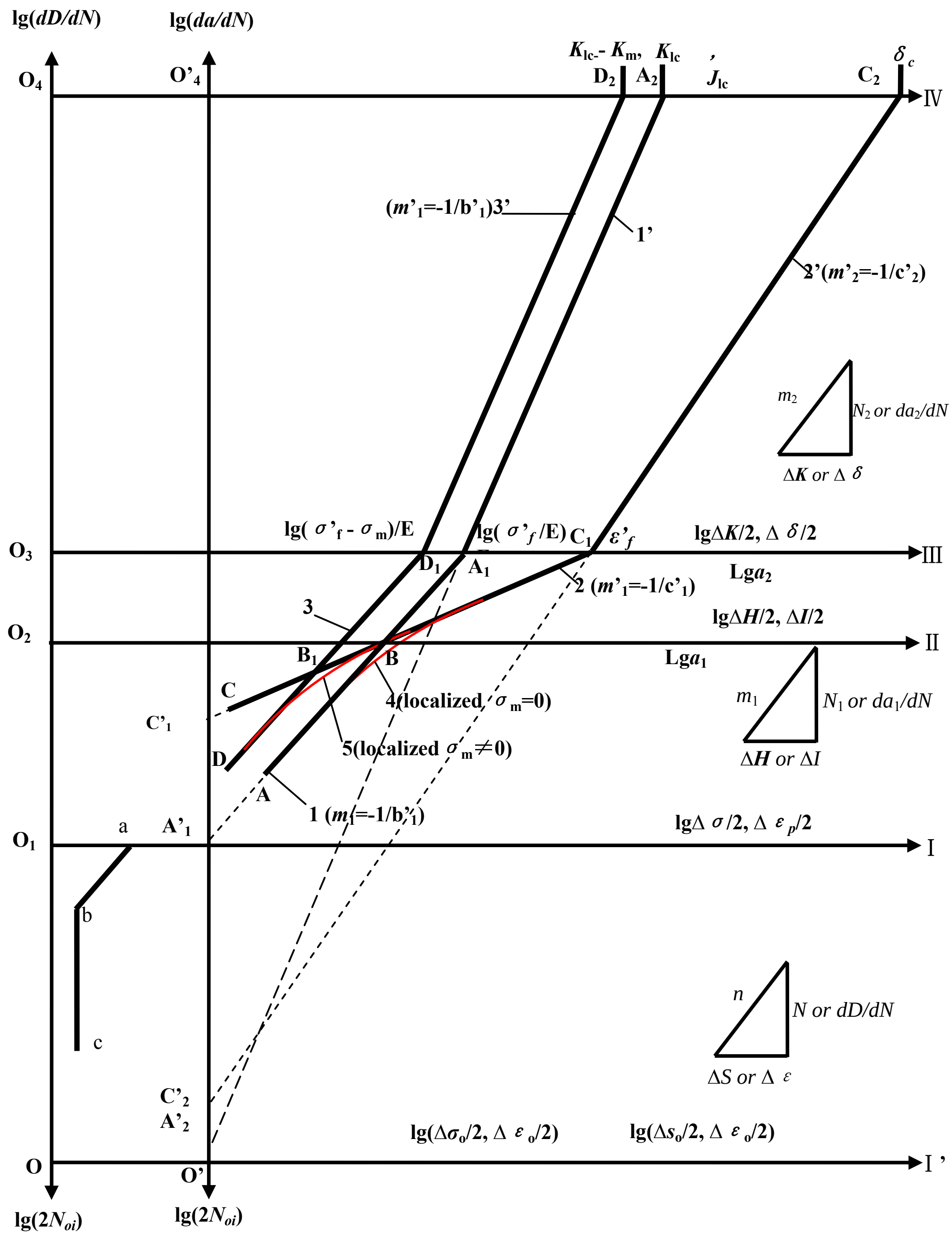

Fig. 1 Bidirectional combined coordinate system

Based on figure 1 and above function design of present procedure, their main calculation equations, curves, material constants, their physical and geometrical meanings and their correlations of each other at each stage are all displayed in reference [1, 2, 3], and their calculation methods of damage evolving rate, crack growth rate and relative life in whole course are also explained in it. These correlations include： between positive and inverted direction in coordinate system; between positive and minus sign of the symbols in equation; reciprocal relation between the mathematic signs of parameters in equation; between symmetrical cycle and un-symmetrical cycle under loading state. And among the references give also a lot of various relations: between the main equations, between the each curve, between the each parameter of elastic or plastic material at crack forming stage were showed in reference [2]; of elastic or plastic material at crack growth stage in reference [3]; of elastic-plastic material at crack forming stage and crack growth stage in reference [4,5,6,7]; the expressions and its method of the life estimations in whole course under multilevel loading from un-crack to crack forming till fracture are also explained in reference[14].

4. Systemic design

4.1 Flow of the program

The programs are developed by means of the C++Builder6.0 and SQL Server 2000. Fig. 2 is a simple flow of the program among their intersectional correlations on fatigue-damage-fracture [1, 2].

Designs of the modules and functions of the systemic main parts are as follows.

1). Calculating modules of the crack forming stage

|-Calculations of strength and deformation.
|-Calculations of stress and strain.
|-Calculations of tension or compression .
|-Calculations of shear and torsion.
|-Calculations of bending.
|-Other calculations.
|-Fatigue damage calculations of elastic and plastic material [4,5,6,7].
|-Damage calculation of symmetrical cyclic loading.
|-Damage calculation of un-symmetrical cyclic loading.

2). Calculating modules of the crack growth stage.

|-Calculations of strength and deformation at crack tip [8].
|-Calculations of□-type,□-type, □-type and mix-type stress intensity factor at crack tip [9,10].
|-Calculations of J-integral.
|-Calculations of crack tip open displacement.
|-Fatigue life calculations of elastic and plastic material. .
|-Damage calculation of symmetrical cyclic loading.
|-Damage calculation of un-symmetrical cyclic loading.

3). Calculating modules of damage and life in the whole process

|-Fatigue damage calculations of elastic and plastic material.

|-Damage calculation of symmetrical cyclic loading.
|-Damage calculation of un-symmetrical cyclic loading.

4). Calculating module of typical parts

|-Calculating procedure of a combinatorial cylinder [11].
|-Calculating procedure of a crankshaft [12].
|-Calculating procedure of a connecting bar [13].
|-Calculation of total life in whole process under many stages loading[14].

5). Databases modules.

|-Databases of material chemical component.
|-Databases of material mechanical capability.
|-Databases of calculating equations and curves.

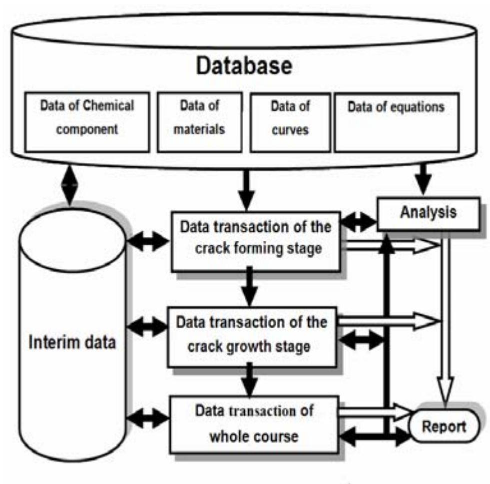

Fig.2 simple flow of program

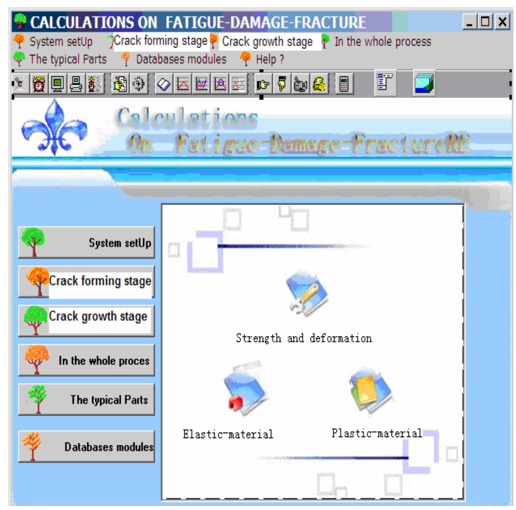

Fig.3 main interface of program

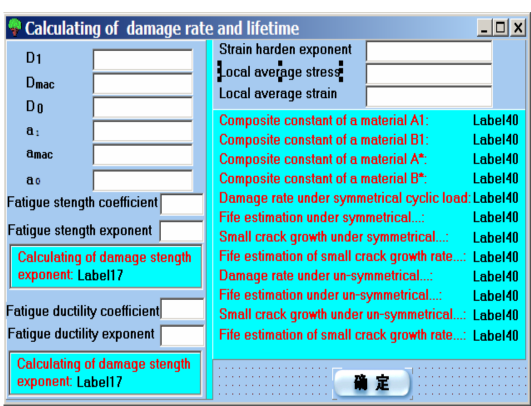

Fig.4 Calculation interface for data input

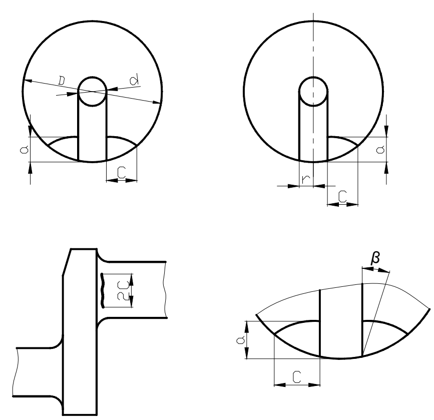

Fig.5 Calculation positions of Fracture mechanics for a crankshaft

4.2 Design of the interfaces

The programs are designed with various interfaces which are accomplished by function desire mentioned above for each module under varied design condition. The software has made a lot of multifarious interfaces, which include the main interface (Fig.3), calculation interface of data input (Fig.4), of table forming, of curve plotting, of database query and calculation interface of data, etc. and the Fig.5 is the calculation positions of fracture mechanics of a crankshaft with various shape cracks.

5. Discussions

Want to actualize the calculations for the strength and the life at each stage or in whole evolving process of material behaviors, it must solve following key problems:

1. Base on the standpoint for the crack size a also as a damage variable like the damage variable D, the damage parameter D in each equation for calculating damage rate and various history life N_{oi} may be converted into another parameter with physical meaning as crack size a, and It should be necessary and also possible for concretely describe the damage of a material. Here must be ordaining that $D_0 < D <= D_{mac}$, their units are all values of dimensionless; and $a_0 < a <= a_{mac}$, their units are all millimeter. If D_{mac} =1.0, then the ratio $a_0 / a_{mac} < a_1 / a_{mac} <= a_{mac} / a_{mac} = 1.0$. So the D and a can be treated as a relation of equivalent value.
2. Must solve the transforming paths and methods between the correlation each other for some parameter, that is the relations between the nominal stress and local stress, the damage variables D and a_1 ,Material constants m_1, m'_1 and b_1, b'_1 , m_2, m'_2 and b_2, b'_2 and their calculation units etc in different equations with equivalent relation.
3. Want to make connects each other between the calculation equations and their curves at each stage. It Should also solve some transforming paths and methods between the threshold levels at the critical point on abscissa axes $O_1\mathrm{I}$, $O_2\,\mathrm{II}$, $O_3\,\mathrm{III}$ and $O_4\mathrm{IV}$ (in Fig. 1). And solve the paths and methods of problems above mentioned, it had been explained in the reference [8]. Thus, it can calculate the all strengths and life in whole course to use same dimension by means of a_1 and a_2, or also can calculate the all ones in whole course to use zero dimension D_1 and D_2. So it can offer a new calculation method for some structures from a material damage to fracture.

6. Peroration

Connect their intersectional correlations each other at each stage and in whole process are very complex problems for so much of calculation equations, curves, material constants and their physical and geometrical meanings. But base on above analysis and functions design of present programs, for discussed problems must be under the local calculations and same nominal stress at the crack forming and crack growth stage, by means of the bidirectional combined coordinate system, make well transforming transaction between the variables, materials constants, stress and strain in equations for those having equivalent relations, and adopt software technique, systematically design applied programs of calculation, analysis and their databases etc, thus it can accomplish connections among their intersectional correlations of material behavior at each stage on fatigue-, damage-, fracture disciplines. Thereby can offer a scientific tool and method for a mass of calculations of structures and materials in engineering domains; predict it would be understand, accepted and applied widely to the cross-referencing among each branch disciplines, for the economizing fatigue-damage-fracture testing bankroll, also have practical significance.

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