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Research on Crack Propagation Simulation of Mental Construction of Bridge Crane Based on Damage Mechanics

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Abstract

Based on continuum damage mechanics theory, fatigue crack propagation of girder of founding crane was researched under cyclic stress. According to the damage fatigue experimental data of Q345, undetermined parameter of damage model was got, and fatigue damage model of girder of founding crane was deduced under cyclic stress. Based on this research, with the method of live-dead element of finite element analysis, expansion process in the crack producing stage of founding crane was simulated, and crack propagation process in the different temperature was compared, what's more, the influence of temperature to the crack propagation has been analyzed.

Keywords: *Damage Mechanics, Damage evolution model, Finite element, Casting crane, Crack propagation*

1. Introduction

It is a common way to analyze the crack propagation with the fracture mechanics theory in the crack research. The crack and its expansion law have been researched widely in the classical fracture mechanics [1-5]. In the methods of fracture mechanics research, firstly suppose the conditions of crack exist, to seek the length of crack, inherent resistance of the crack growth that the materials resist, and ration relation among stress of structural failure caused by crack expanding in high speed. Therefore, the defects of objects in the classical fracture mechanics just show the existence of bizarre defects, and mental construction of crane has been working many years before appearance of cracks. Calculating with the fracture mechanics method is the telophase life-span of mental construction of crane, so the evaluation of prophase life-span of mental construction of crane (stage of crack producing) has defects with the fracture mechanics methods. However, the researching contents of the damage mechanics are continuous distribution defects and various defects of dislocation, micro-cracks and micro-holes in the objects, which are called damage. In the macroscopic views, they spread all over the whole object. The happening and development of these defects manifest the distortion and breakage of materials. With the various loading conditions, the damage mechanics researches destructive process and laws caused by the development of damaging distortion of objects.

2. Fatigue Damage Theory

According to damage mechanical theory [6], damage variable D stands for the expansion of micro-void. And Micro cracks lead the material into the damage real effective bearing area $\tilde{A}$ which is denotes as decrease degree. That's to say, formation

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and extending of micro-cracks and micro-gaps result in cross-sectional area A of test specimens reduce to practical effective loaded area $\tilde{A}$; Meanwhile, the diminution of effective loaded area results in the increase of practical stress, which leads to degradation of mechanical property of materials. According to the definition of damage mechanics assume:

$$1 - D = \tilde{A} / A \tag{1}$$

The cross section effective bearing area reduced, lead to the increase of effective stress, effective stress can be expressed as:

$$\tilde{\sigma} = \sigma / (1 - D) \tag{2}$$

The fatigue damage is caused by the material with lower ultimate strength under the alternating load. Some local area or wide area first yield, plastic deformation of high degree is found in a local region, it is a kind of the fracture process of its trans-granular fracture.

Based on continual damage mechanics theory, fatigue damage is expressed by dissipation potential function. This text use X. H. Yang, N. LI, *et al.*, proposed dissipation potential model [7], to express the degree of damage accumulation:

$$\phi = \frac{Y^2}{2S_0} \frac{\dot{r}}{(1 - D)^{a_0}} \tag{3}$$

Where:

S_0 ——materials relates to the temperature constant;

a_0 ——material constant;

$\dot{r}$ ——each cycle of accumulated plastic strain;

According to the literature [8], the extent of damage accumulation is described by function $\beta(\sigma, T)$ instead of a_0; experimental cyclic load is pulsation cycle, σ is expressed by the biggest stress 'σ_{max}', Expression (4) is

$$\phi = \frac{Y^2}{2S_0} \frac{\dot{r}}{(1 - D)^{1-k(\sigma_{max}, T)}} \tag{4}$$

Literature [9] explained the theory of fatigue damage in detail. Assuming that plasticity deformation leads to interior damage and energy consumption, so dissipation potential function is

$$\phi = \phi_P(\sigma, \sigma_Y, R, D) + \phi_D(Y, r, T, \varepsilon_e, D) \tag{5}$$

Where:

σ ——stress tensor;

σ_Y ——Material the initial yield stress;

R ——Isotropic cumulative plastic strain hardening parameters;

Y ——strain energy release rate;

r ——accumulated plastic strain;

T ——absolute temperature;

ε_e ——elastic strain tensor;

ϕ_P ——elastic strain tensor, in view of the loss of plastic parts;

ϕ_D ——dissipation part of the damage.

In view of the damage dissipation part ϕ_D, damage kinetics law can be expressed as:

$$\dot{D} = -\frac{\partial \phi_D}{\partial Y}\dot{\lambda} = -\frac{\partial \phi}{\partial Y} \tag{6}$$

Substituting equation (4) into (6), we obtain

$$\dot{D} = (-\frac{Y}{S_0})\frac{\Delta \dot{r}}{(1-D)^{1-k(\sigma_{\max},T)}} \tag{7}$$

The strain energy release rate is

$$Y = -\frac{\sigma_{eq}^2}{2E(1-D)^2}R_V \tag{8}$$

Here

$$\Delta\tilde{\sigma}_{eq} = \frac{\sigma_{eq}}{1-D}.$$

Based on strain equivalence principle [10], the stress-strain relations is

$$\Delta\tilde{\sigma}_{eq} = K\Delta r^{m} \tag{9}$$

K , m ——constant

Substituting (8) and (9) into (7), Equation (10) can be obtained:

$$\dot{D} = (-\frac{K^2 R_V}{2ES_0})\frac{\Delta r^{2m}}{\left[(1-D)\right]^{1-k(\sigma_{\max},T)}}\Delta\dot{r} \tag{10}$$

Integrating equation (10), and $D = N/N_f$, the boundary conditions $D|_{N=N_0} = D_0, D|_{N=N_f} = 1$ are generated,

$$D = 1-(1-D_0)[(1-N/N_f)]^{k(\sigma_{\max},T)} \tag{11}$$

Equation (11) is deduced based on damage mechanics theory of fatigue damage evolution model.

3 The Application of Damage Mechanics Theory in the Finite Element Analysis

First of all, define the Fatigue damage evolving model formula (11), introduce the damage evolving equation into the constitutive relation, equilibrium equation, geometrical relationship, initial condition and boundary condition. At the moment, damage field, stress field, strain field act on the unit together. But if the coupling of damage field and stress field, strain field is considered in the all units, and the cycle life is very long, the calculating work will consume much time. Now with the method of effective stress in the damage mechanics, the procedure is:

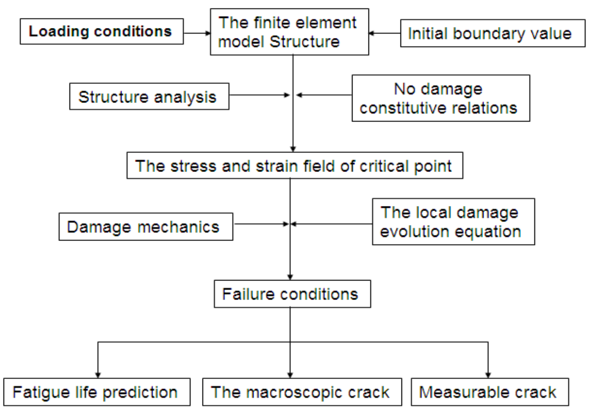

Figure 1. Schematic Diagram of Structure Damage Analysis

Test parameters based on one-dimensional stretching which are got in the fatigue experiment, according to the three-dimensional stress model of damage equivalent stress put forward by Lemaitre [11].

$$\sigma_{deq} = \bar{\sigma}\sqrt{\frac{2}{3}(1+\mu)+(1-2\mu)\left(\frac{\sigma_H}{\bar{\sigma}}\right)^2} \qquad (12)$$

$\bar{\sigma}$ ——Von Mises equivalent stress

σ_H ——hydrostatic pressure

μ ——Poisson ratio

Stretch and compress have different influence to the damage evolution, because of crack closing effect. According to the different state of stretch and compress, amendatory damage equivalent stress is different.

Stretch $$\sigma^*_{deq} = \sigma_{deq} \qquad (13)$$

Compress $$\sigma^*_{deq} = -\left(\frac{1-D}{1-hD}\right)^{1/2}\sigma_{deq} \qquad (14)$$

To the complicated components, the damage caused by different stresses is different, because the stress of every component is different. The finite element method should be used to calculate damage field, which is to calculate the damage of every unit. Using damage process of unit simulates destructive process of components. Unit damage will be got by accumulating every cyclic damage increment. After one circulation, the damage increment of unit is the superimposing of fatigue damage increment and creep damage increment. From the damage evolution formula, damage increment of the unit N circulation is related to the damage caused by unit N-1 circulation (expressed by D_{N-1}), D_{N-1} takes the place of D, damage increment ΔD_N caused by the unit N circulation is solved by numerical integration, therefore, after N circulations, the accumulating damage of unit is $D_N = D_{N-1} + \Delta D_N$, when N =0, the initial damage of unit is D_0, its value is determined by initial situations of components.

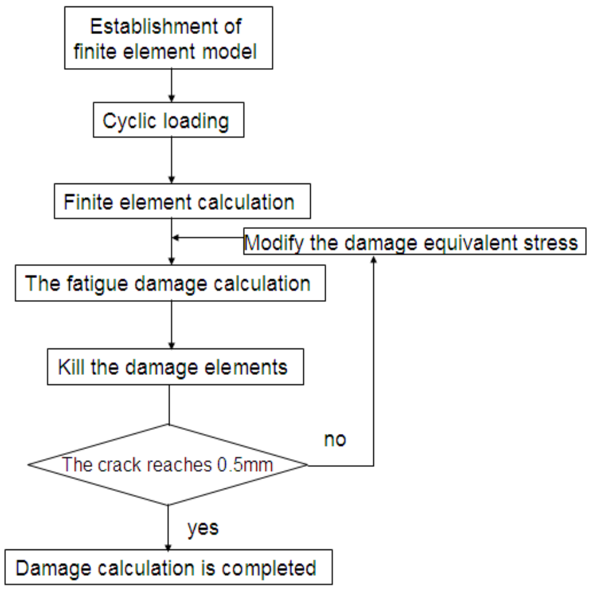

Figure 2. Flow Chart of Structure Damage Program Design

4. Experiment Result Analysis

The test material is Q345 which is commonly used in crane， test conditions for stress control, pulsation cycle, Sine wave load. Before the test, keep samples in the furnace for 30 minute. The environment is atmospheric for laboratory. The load frequency f = 0.3 Hz when have stretch meter, the load frequency f = 4 Hz when haven't stretch meter. At the same temperature $420°C$ under different stress level and the same stress level (0~480MPa) Cycling test under different temperature between $15°C$ and $420°C$.

4.1. The Analysis of the Experimental Data under the Same Stress Level (0~480mpa) and the Different Temperature

Table 1. Same Stress Level (0-480 MPa) Data at Different Temperatures

parameter / test specimen	D_0	k	N_f / cycle	T / °C
1	0	0.03993	2571	15
2	0.0206	0.04994	3024	100
3	0.0108	0.07548	24792	200
4	0.0174	0.12222	61192	250
5	0.0198	0.01528	287366	300
6	0.0115	0.04036	84104	375
7	0.0168	0.03173	38875	400
8	0.0104	0.02779	8341	420

By the data can be seen in table 1, the Stress cycle life maximizing at $300°C$, Now in 300, With two curve fitting in $15-420°C$.

4.1.1. Damage Model in $15-300°C$

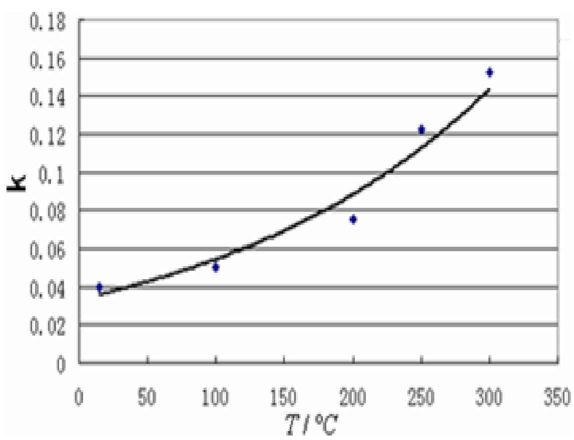

Figure 3. T and k Curve Fitting at $15-300°C$

$k = 0.0335e^{0.0048T}$
R2 = 0.959

$$D = 1-(1-D_0)(1-N/N_f)^{0.0335e^{0.0048T}} \quad (17)$$

4.1.2. Damage Model in $300-420°C$

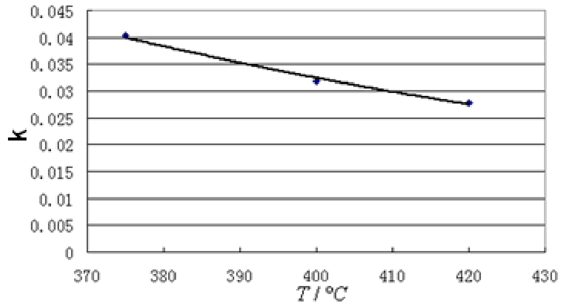

Figure 4. T and k Curve Fitting at $300-420°C$

$$k = 0.9143e^{-0.0083T}$$

$$D = 1-(1-D_0)(1-N/N_f)^{0.9143e^{-0.0083T}} \quad (18)$$

R2 = 0.9897

4.2. The Test Data of the Same Temperature $420°C$ under Different Stress Level

Table 2. Different Stress Levels of Test Data at $420°C$

parameter / test specimen	D_0	k	N_f / cycle	σ_{max} / Mpa
1	0.0134	0.04525	320614	0~420
2	0.0036	0.04438	238362	0~430
3	0.0262	0.04136	144743	0~440
4	0.0142	0.03963	91863	0~460
5	0.0307	0.0328	27302	0~470
6	0.0104	0.02779	8341	0~480
7	0	0.02319	2188	0~490

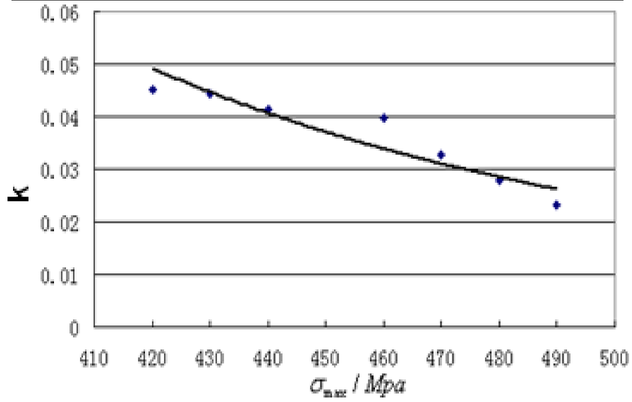

Figure 5. σ_{max} and k Curve Fitting at $300-420°C$

$$k = 2.2514e^{-0.0091\sigma_{max}}$$

R2 = 0.8845

$$D = 1-(1-D_0)(1-N/N_f)^{2.2514e^{-0.0091\sigma_{max}}} \quad (19)$$

4.3. 16MnR Mechanics Performance Test Data at Different Temperatures:

Table 3. Different Temperature and Yield Strength/Ultimate Strength Test Data

temperature $/°C$	σ_s / MPa	σ_b / MPa	φ / %
20	378	582	58
100	312	516	63
200	319	528	56
300	283	576	52
400	233	527	63
420	238	517	70.5

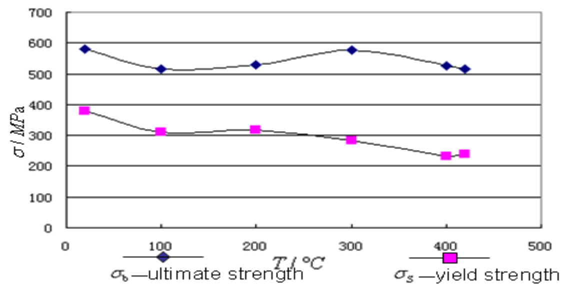

Figure 6. Different Temperature and Yield Strength/Ultimate Strength Curve Fitting

The ultimate strength and temperature fitting function relation:

$$\sigma_b = 4.072192199248056\times10^{-10}T^5 - 4.412721256265577\times10^{-7}T^4 + 1.544129660087676\times10^{-4}T^3 - 0.01717947799185T^2 - 0.17836192042617T + 5.912730263157935\times10^2 \quad (20)$$

R2 = 0.9671

Suppose the influence of σ_{max} 、T to function k（σ_{max} ，T ）isn't linking .In order to do math processing conveniently, following form of linear superposition is assumed further.

$$k（\sigma_{max},T）= k（\sigma_{max}）+ k（T） \quad (19)$$

4.3.1. $15-300°C$ Damage Model

$$D = 1-(1-D_0)(1-N/N_f)^{2.2514e^{-0.0091\sigma_{max}}+0.0335e^{0.0048T}} \quad (20)$$

4.3.2. $300-420°C$ Damage Model

$$D = 1-(1-D_0)(1-N/N_f)^{2.2514e^{-0.0091\sigma_{max}}+0.9143e^{-0.0083T}} \quad (21)$$

5. Example Analysis

Take the 180T founding crane as an example, the dangerous point in the joint of girder and middle section of crane is being analyzed. In Figure 7, the dangerous point 1 is limit inferior location of crane web that corresponds to bonding point of Major separator. The damage field and stress field, strain field are linked only in the dangerous point of crane girder.

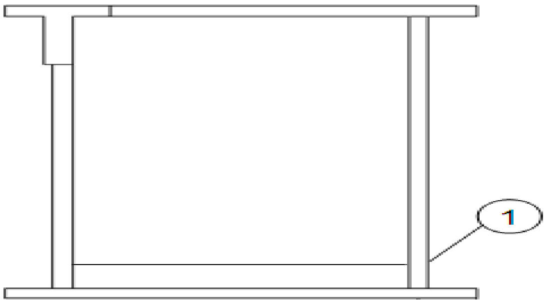

Figure 7. Sectional View of Crane Girder

5.1. The Crack Propagation Process of Dangerous Point 1in the Different Temperature

Figure 8 and Figure 9 are the crack propagation process in the different temperature respectively, Y-axis is the crack propagation dimension L_c, unit is mm, X-axis is cycle index of loading.

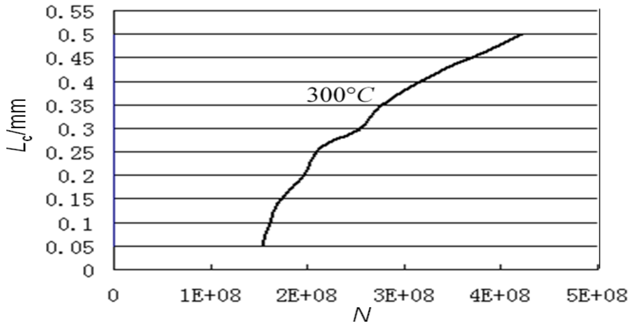

Figure 8. The Crack Propagation Process at $300°C$

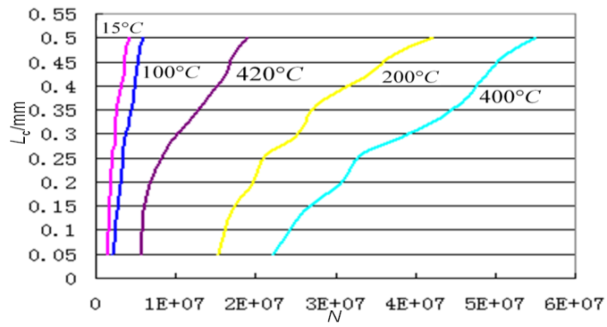

Figure 9. The Crack Propagation Process at the Temperature $15°C$、$100°C$、$200°C$、$400°C$ and $420°C$

5.2. The Crack Propagation Simulating Process in the Finite Element Model at $200°C$

Temperature is an important factor that affects the strength of materials. $300°C$ is the more remarkable of the strength of dynamic strain aging (DSA), DSA curbed the development of cyclic creep and cyclic softening effectively, meanwhile the cycle life is greatly improved, at the moment it reaches a peak.

When the temperature deviates from the DSA temperature range, serious cyclic creep and cyclic softening emerged. Cyclic creep and fatigue interact which leads to the reduction of life expectancy.

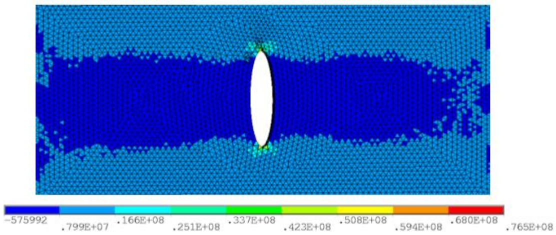

Figure 10. The Crack Propagation at N=1.6532E+07

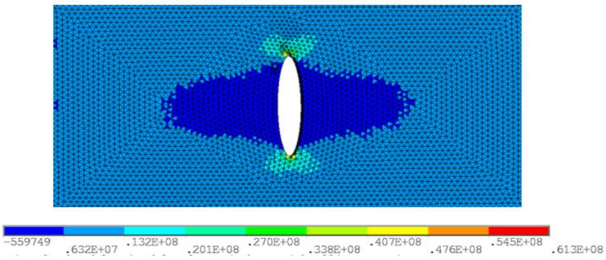

Figure 11. The Crack Propagation at N=2.2586E+07

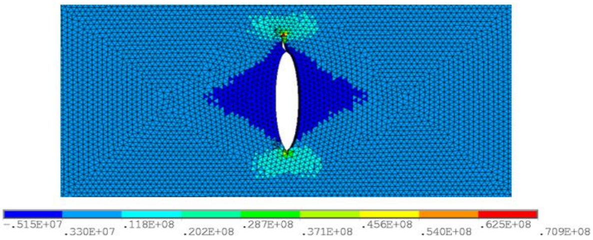

Figure 12. The Crack Propagation at N=2.9673E+07

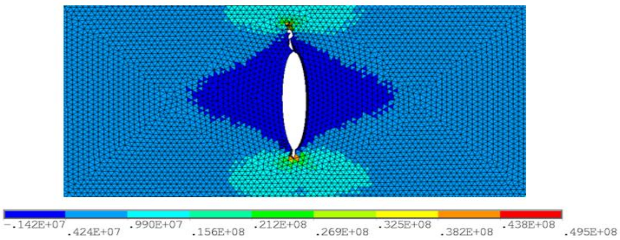

Figure 13. The Crack Propagation at N=3.2389E+07

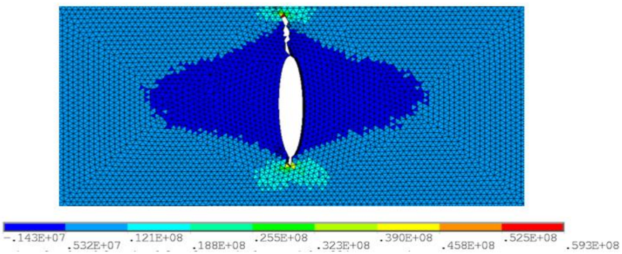

Figure 14. The Crack Propagation at N=3.9667E+07

As can be seen from the results of finite element analysis, with the increase of load frequency, crack along the direction of extension of partition, due to the stress singularity at the crack tip region, stresses in the crack tip stress value is significantly higher than that in other area value, the area of the unit first killed, the formation of crack extension direction.

6. Conclusion

In the life evaluation of crane, the crack initiation stage accounted for about 80% of all life, the life assessment of the crack initiation stage is extremely important. On the basis of damage mechanics theory, the paper simulates the propagation of crane during the crack initiation stage, this method has clear physical meaning and good theoretical basis, and it has a very strong guidance for engineering application.

6.1 The life-span in the crack initiation stage has been simulated in the finite element model, when the crack expands to 0.5mm (measured crack dimension), this crack dimension is regarded as upper limit dimension in the crack producing stage, at the moment, the life-span is prophase life-span.

6.2 Link the temperature field, stress field, strain field and the damage field. Describe the damage situation of mental construction of crane under cyclic loading.

6.3 Simulate the crack propagation laws of crane in different temperature with fatigue experimental data in different temperature.

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