SOME APPLICATIONS OF FRACTURE MECHANICS IN CHINA

He Qingzhi (何庆芝)
Beijing Institute of Aeronautics and Astronautics, China

Fracture mechanics has been and will continue to be a powerful tool in fracture-safe design of new engineering structures and in safe assessment of "older" ones. Since the introduction of fracture mechanics into China in the late 1960s, its application has extended to almost every field of technology. Many scientists and engineers in China have paid much attention to the fracture control of large structures such as in ships, railway vehicles, airplanes, storage tanks, pressure vessels and rocket casings, the failure of which would cause considerable economic losses and, most likely, the loss of many human lives.

In the present paper no attempts are made to give an overall review of all these applications, but only some examples are presented here.

FRACTURE ANALYSIS AND SAFETY EVALUATION OF FLAWED ROTOR FORGING OF 300 MW STEAM TURBINES

Fracture analysis and safety evaluation of revolving mechanism, such as steam turbine rotors, generator rotors, waterturbo generators and their vanes, axles, impellers of gas turbines, etc. have been conducted in China for many years. In the 1976—1977 time period, according to the proposal of the Ministry of Machine Building Industry, engineers and scientists

---

Co-authers:

Wu Qingke (吴清可): Zhengzhou Research Institute of Mechanical Engineering. Li Zezhen (李泽震): General Machinery Research Institute. Liu Shuhua Chinese Academy of Railway Science. Lin Jizhong : Chinese Academy of Railway Science of sixteen institutions formed a technical team to perform fracture analysis and safety evaluation of a flawed rotor forging of a 300 MW steam turbine. Experiments conducted included: determination of FATT, K_{1c}, J_{1c} with different types of specimens, da/dN under different frequencies, and K_{th}, etc. Some of the results are shown in Fig. 1, 2 and 3. In order to calculate the stress intensity factors properly under complex stress conditions, a tensile-torsional test was conducted and the test results were compared with the theoretical criterion, which is shown in Fig. 4 and 5. In this analysis, the alternating normal and shear stresses caused by centrifugal force and dead-weight of the rotor, residual stress, thermal stress and torsional stress, were measured and calculated. Stress intensity factors K_I and K_{III} are shown in Fig. 6 and 7. Then the flaw allowance and operational life of the 300MW steam tubine were predicted. This was reported in more detail in Ref. [1].

In recent years, the probabilitistic fracture mechanics has been adopted by ZRIME in fracture analysis and reliability design of structures, for instance, in the analysis of the ladle trunnion. It was shown that the K_{1c} values of different ladle materials follow a normal distribution and so does the flaw dimensions which were obtained from non-destructive detections by the factories in a time period of 16 years. In the formula of crack propagation rate $\frac{da}{dN} = C(K)^n$, C and n are statistically related. It was also found by tests of over 20 materials that in the expression $C = A \cdot n^B$, n also follows a normal distribution[2]. Using the Monte Carlo method, the life-time of the ladle trunnion was simulated by computer, and the logarithmic normal distribution was proved to be a good method to describe the life-time distribution of ladle trunnion, as is shown in Fig.8 and 9. More details are presented in Ref. [3].

DAMAGE TOLERANCE EVALUTION OF AIRPLANE STRUCTURES

The damage tolerance design philosophy was not introduced into China until the late 1960s. However this concept was soon employed in the development of new aircraft and in reexamination of older aircraft and "in-service" aircraft.

In the following some examples of applications of fracture mechanics in this field are presented.

1. Investigation on the Damage Tolerance Characteristics of the Primary Structure of the Transport Aircraft Y-10

The preliminary design of Y-10 began in 1970 in Shanghai. In the early phase of the structure design, it was decided that the damage tolerance design philosphy should be used. Since verificaton of the damage tolerance criteria for most of the structures must be performed analytically, method of analysis and some basic material and structural data must be available. In the last ten years, investigations on cracked stiffened panels, flat and curved, were performed in order to develop methods for predicting the residual strength and the crack growth life of this type of structures. In studying the fracture behaviour of such typical structures both analytical and experimental methods were used. Some 40 specimens of flat stiffened panel with central crack were first tested at the Institute of Aeronautical Materials, Beijing, during the 1974/1975 time period, and then some full-scale specimens simulating the real structure used in Y-10 aircraft wing were tested at the Aircraft Structural Strength Research Institute. In these experiments both residual strength and crack propagation behavior were studied. It was found that in order to get satisfactory prediction of the residual strength of the cracked structure, the plasticity of the stiffeners and fasteners must be taken into account.

Another task in parallel with the above mentioned was a study on the fracture and fatigue characteristics of fitting and connections of the wing and fuselage structures in Y-10 aircraft.

2. Durability and Damage Tolerance Assessments of Older Aricraft

(1) In the year 1973, on some fighter airplanes serious cracking problems were encountered in landing gear welded structural members. In order to remove this trouble, a special technical group was formed. Problems to be solved by this group were : (a) prediction of the fatigue life of the original un-cracked member, (b) prediction of the residual life of the cracked member, (c) development of a life extension plan.

Since most of the cracks occurred at the vicinity of the welded area, if the members are to be repaired by welding after the crack is cleaned up, a question that should be answered first is whether the alloy (30CrMnSiA and 30CrMnSiNi$_2$A) can be re-welded many times (i.e. repeat the welding at the same place more than two times). After working at this problem for some two years, they found that the cracked parts can be re-welded several times without appreciably changing the fracture toughness of the material provided the welding technology is appropriate. They also found that for the same member the sum of the fatigue life after each re-welding is approximately the same as the total fatigue life of the base metal. Test results of specimens and full size landing gears confirmed this conclusion. It is evident that this re-welding technology is profitable, for otherwise the cracked parts have to be replaced by a new one which would be very expensive.

(2) In recent years, on some cargo aircraft small cracks of the size $a_0=0.2$ mm were found near the window along radial direction. It is required to examine this problem and answer the question: could the airplane continue to fly safely before the next overhaul?

Two tasks were performed in this investigation.

The first task was the development of ground-air-ground and air-air load spectra which were based on data obtained from the same type of airplane flying along the air line between Chengdu and Lhasa. The load spectra were then converted to stress spectra of the specific structure to be examined.

The second task was to perform the crack growth calculation so that the residual life (for the crack to propagate from $a_0=0.2$ mm to a_c) of the structure could be obtained. The method of life prediciton developed by some Chinese researchers will be presented later. Calculations show that the residual life of the cracked part is not less than 9,000 flight hours, while the specified overhaul interval is 6,000 flight hours. These damaged airplanes have already flown safely for 5,000 flight hours.

(3) Most of the older military airplanes of Chinese Air Force were designed more than 20 years ago when the damage tolerance design philosophy was not introduced into aeronautical engineering yet. For flight safety it seems necessary to conduct a damage tolerance assessment of these older airplanes. Since this was such a huge task that it could be accomplished only by a large technical team, the scientists and engineers of Xian Aircraft Cumpany and Aeronantical Structural Strength Research Institute tried to conduct only a test programme on some of the primary structures of an airplane and to determine whether the structure can fulfill the residual strength and life requirements. The structure under consideration was the main spar of the wing. Testing loading spectra were developed on the basis of flight load spectra, using the equivalent-damage principle during the spectra conversion, i.e. the damage caused by the test spectra loading must be the same as the damage caused by the flight spectra loading. In making the spectra conversion, overload retardation effect was also taken into account utilizing Willenborg's model.

This experimental study showed that the structure of the main spar fulfills the requirements of residual strength and operational life.

3. Some Analytial Method for Life Prediction

In conducting the damage tolerance evaluation of airplane structures, in addition to experimental work and numerical calculations as we have briefly described above, several analytical methods were also developed.

(1) In predicting crack growth life of a structure under spectrum loading, the retardation effect due to overload must be taken into account. Models for predicting the overload retardation effect were proposed by several authors. Huang and Liu[4] suggested a semi-linear Willenborg Model. The equation relating the retarded crack propagation rate to the original rate before overload is

$$\left(\frac{da}{dF}\right)_{ret} = \left[\frac{1-\lambda(r-1)}{1-R}\right]^n \left(\frac{da}{dF}\right)_{linear}$$

where $\left(\frac{da}{dF}\right)_{ret}$ and $\left(\frac{da}{dF}\right)_{linear}$ = crack propagation rate per flight with and without overload retardation respectively r = the overload ratio, R = the stress ratio, λ = a factor to be determined experimentally.

Another model was proposed in [5]. Using the concept of effective residual stress, the number of "delayed cycles" following an overlood can be calculated by

$$N_D = \frac{1}{\left(\frac{da}{dN}\right)_0} \int_0^{\Delta a_c} \frac{d\Delta a}{U^n}$$

where $\left(\frac{da}{dN}\right)_0$ is the crack propagation rate just before the overload.

$$U = 1 + \frac{(1-\alpha)}{1-R} - (1-\alpha)\frac{K_{ap}}{K_b}$$

$$= 1 - \frac{1 - \frac{\Delta K_{th}}{\Delta K_b}}{r_c-1}$$

and $n=4$ for aluminum alloy and titanium alloy.

A predicted a-N curve of a specimen under programmed loading block is shown in Fig.10, which was obtained by Tian and Zhang of Shenyang Aircraft Company using the above formula. Their experimental data are also shown in the same figure for comparison.

(2) In predicting the crack growth life under spectrum loading, a cycle-by-cycle integration method is generally used which is very tedious indeed. A close form solution for predicting the residual life under pro-

grammed loading was proposed [6]. It was shown that if the loading block size is small enough (say, 100 flight per block), the retardation effect due to overload can be neglected. The crack growth life of the structure can be predicted by

$$T_c = \frac{\int_{a_0}^{a_c} Y^{-n}(a)da}{\alpha \sum_{i=1}^{p} \sigma_{i_{max}}^{\beta} (\Delta\sigma_i)^{\gamma} N_i}$$

where: T_c is the number of cycles required for crack growth from a_0 to a_c;
α, β, γ are the coeffients in Walker's formula for crack growth rate, and $n=\beta+\gamma$;
p is the number of stress levels in one loading block; $\sigma_{i_{max}}$ and $\Delta\sigma_i$ are the maximum stress and stress range in the i-th stress level respectively;
N_i is the number of cycles of the ith stress level in each block and $Y(a) = \frac{K}{\sigma}$.

(3) M.G. Yan, M.D. Gu and T.K. Zhang of Institute of Aeronautical Materials have studied the crack growth retardation behavior and fatigue life prediction in structural materials and evaluated the crack growth retardation models proposed by Wheeler, Willenborg, Maarse and Matsuoka respectively[7]. Based on the data obtained from their experiments under constant amplitude cyclic loading with a series of single overloads at different crack length and spectrum loading, comparisons were made with the predicted a-N curves. They found that the Wheeler model by adjusting the exponent m and the Matsuoka model could give rather satisfactory results. The Willenborg and Maarse models would also give satisfactory predictions if same modifications were made. In the original work of Willenborg the overload affected zone is assumed to be equal to the plastic zone due to the overload which is determined by $\gamma_p = \frac{1}{\alpha\pi}(\frac{K}{\sigma_{ys}})^2$, $\alpha=2$ for pure plane stress condition and $\alpha=6$ for pure plane strain condition. Y.K. Zhang suggested in a paper[8] that the value of α should be calculated by $\alpha = \frac{6}{1+2s}$, where $s = (\Delta K-\Delta K_{th})/(1-R)K_c$ may be regarded as the fraction of the plane stress region occupied in the fracture surface.

In the same paper Zhang also suggested that in using the Maarse model the constant C* and N* in the equation

$$\frac{da}{dN} = C^*(\Delta K_{eff})^{N^*}$$

could be determined by

$$N^* = N$$

$$C^* = C\left(\frac{1-R}{1-\frac{P_{op}}{P_{max}}}\right)^n$$

where c and n are material constansts obtained by the Paris law under constant amplitude cyclic loading.

SAFETY ASSESMENT OF PRESSURE VESSELS

The failure of pressure vessels would in general cause serious losses, it is necessary to perform safety assesment for pressure vessels now being in operation in different field of industry, and to determine whether they could continue to be operated safely. In recent years some hundreds of pressure vessels were inspected by NDI method. If crack were discovered in them, the residual strength and crack propagation life were evaluated by fracture mechanics methodology. One example of these investigations is described briefly below.

Thousands of circular cracks along the longitudinal weld seams were discovered in six ammonia synthetic reactors. Inspection by scanning electromicroscope showed that these were hydrogen induced cracks. The vessels were of multi-layer construction with a core cylinder and eleven layers of wrapping plates. The core cylinder was made of 15 MnV plate of 19mm thickness, the wrapping plates were made of 14MnMoVB plate of 6mm thickness. The diameter is 1010mm and total length is 13,800mm, and design pressure is 33 MN/m². In order to perform the safety evaluation, the following programme of analysis and experiments were conducted jointly by GMRI (General Machinery Research Institute), SBW (Shanghai Boiler Works) and Zheijiang University.

1) Determination of the fracture toughness

The crack initiation COD values of 14MnMoVB, including the base metal, fusion boundary and the heat affected zone were measured. For example, the crack inition COD values of the base metal were δ_c=0.066, 0.065, 0.064, 0.061.

2) Testing of crack initiation pressure and bursting pressure with model vessels

GMRI performed some tests on small model vessels. Crack initiation pressure and bursting pressure were predicted by COD method. One of these models was a single layer model vessel with a diameter of 200 mm and length of 500 mm, with a wall thickness of 6 mm. When the initial crack a_0=30.75 mm, the tested results and predicted value were as follows

	Predicted	Measured
Crack initiation pressure	8.7 MN/m²	9.0 MN/m²
Bursting pressure	21 MN/m²	21.3MN/m²

3) Investigation of the crack propagation of the vessel material and the vessel.

It was found by specimen testing that the crack propagation rate for this material can be expressed as

$$\frac{da}{dN} = 1.96 \times 10^{-10}\ K^{3.1}\ \text{mm/cycle} \quad (\text{The unit of } \Delta K \text{ is kg/mm}^{3/2})$$

The service life of the vessel was predicted using the above equation. The predicted life is

$$N = 24.6 \times 10^4 \text{ cycles}$$

which indicated that the vessel can be operated safely for a long time.

4) A full-scale pressure vessel of 1010 mm diameter with seven cracks was tested under internal pressure. After 20,000 cycles of operation, the measured crack increments of these existing cracks in different locations were in the range 2Δa=2–4 mm, while the predicted values were 2Δa=3∼4.8 mm.

Other safety assessment of high pressure vessels were also conducted by the institutions mentioned abvoe. An ammonia seperator with $15.5 \times 100^{\text{mm}}$ surface crack, a high pressure boiler of 1800^{mm} in diameter, a pressure vessel of 1400 mm in diameter, four 200m³ spherical storage containers, etc. were analyzed and tested in recent years. After careful investigation, most of these vessels were allowed to operate further for many years but inspection must be made periodically. This saved millions of yuans.

FRACTURE ANALYSIS OF RAILWAY VEHICLES

In the early 1970s, in routine inspections by ultrasonic detection method, tranverse cracks were found in many shafts of the locomotives and railway vehicles. Careful study showed that these cracks are initiated by stress concentration due to fretting corrosion.

Operation safety demands that the damaged shafts must be re-analyzed by fracture mechanics methodology. For this purpore reliable fracture toughness data and crack growth data must be available. A series of tests was conducted. The specimen material was taken from the broken shaft, its chemical composition and mechanical properties are as follows.

Element	C	Si	Mn	P	S
% weight	0.40	0.23	0.63	0.013	0.030

Stress Ratio R	0.1	0.5	0.77
K_{th}(MN/m$^{3/2}$)	11.2	6.45	4.35

K_{1c} at -40°C = 62.0 MN/m$^{3/2}$

Calculations show that: (a) for a surface crack, the predicted critical depth a_c=200 mm, the mearured true crack depth of the fractured part is nearly the same, (b) if the initial crack depth is less than 7 mm, then under an applied stress σ=8 kg/mm², the ΔK value will be fairly close to the threshold value ΔK_{th}. Therefore the crack propagation rate will be very low.

To verify this conclusion, four locomotives with cracked shaft of initial crack depth a_0= 2∼3 mm were monitored in service. After travelling approximately 300,000 kilometers, the depth a_1 of these cracks were measured. The results are shown in table I

Table I

Shaft No	a_0 (mm)	a_1(mm)	S(10^3km)
1	3.0 0.5	6.4	260
2	2.5 0.5	6.2	299
3	2.0 0.5	6.1	275
4	2.6 0.5	6.3	265

Where S is the travelling distance.

The result of this study suggestes that it is possible to double the service life of the shaft. This is very attractive from the economic point of view.

ACKNOWLEDGEMENTS

The authors wish to express their sincere appreciation to Zhengzhou Research Institute of Mechanical Engineering, Aircraft Structural Strength Research Institute, Shenyang Aircraft Company, Academy of Railway Science and General Machinery Research Institute for their help in preparing this paper. The help of Professor Sun of Southwestern Jiaotong University and Professor Zhang of Beijing Institute of Aeronautics and Astronautics and Mr. Liu of Beijing Institute for Labour Protection Research is gratefully acknowledged.

REFERENCES

[1] Fracture Mechanics Analysis of Rotor Forging of a 300MW Steam Turbine (In Chinese), Journal of Mechanical Strength (1978), No. 4, p.1.

[2] Wu, Q.K, et al, A Simplified Method for Determining Material Crack Propagation Rates, Eng. Fract. Mech., Vol. 16, No. 1, P. 141(1982).

[3] Wang, Z.M. et al, Fracture Analysis of a ladle Trunnion (In Chinese), Journal of Mechanical Strength No. 2 1, 13 (1982).

[4] Huang, Y.S. and Liu, X. H. Semi-linear Willenberg Retardation Model (In Chinese), Technical Report No. 239009. North-west Polytechnic University (1980).

[5] He, Q.Z., A New Model for Predicting Overload Retardation Effect in Fatigue Crack Propagation (In Chinese), ACTA Aeronautica et Astronautica Sinica, Vol. 2, No. 2, P. 26 (1981).

[6] Zhang, X. et al, A Close-Form Solution of Crack Propagation Lives (In Chinese), Journal of Aeronautical Material, Vol. I , No. 1, P. 1 (1981).

[7] Gu Mingda et al (1982), An evaluation of overload models on the retardation behavior in a Ti-6Al-4V alloy, Fatigue Eng. Mats & Struct. Vol. 5, No. 2, PP. 167–176.

[8] Zhang Yongkui et al, Modification of Willenborg and Maorse Models and application to the life prediction for a Ti-6Al-4V alloy (In Chinese), Acta Aerorautt. Astronaut. Sinica, 3/2 (1982).

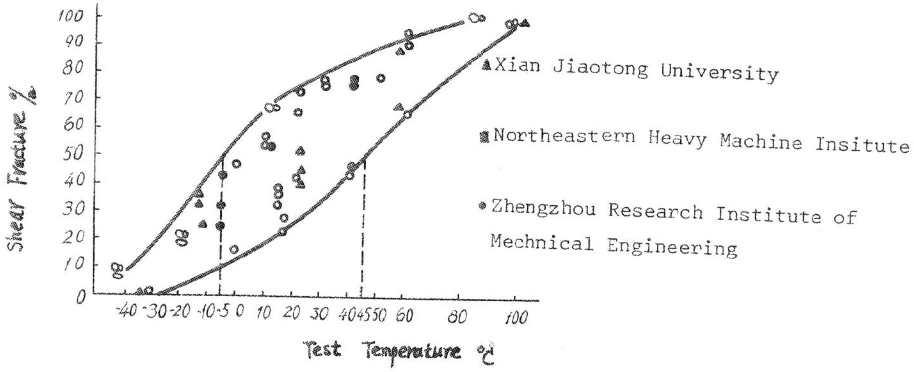

Fig. 1 FATT of the 300 Mw Steam Turbine Rotor Forging

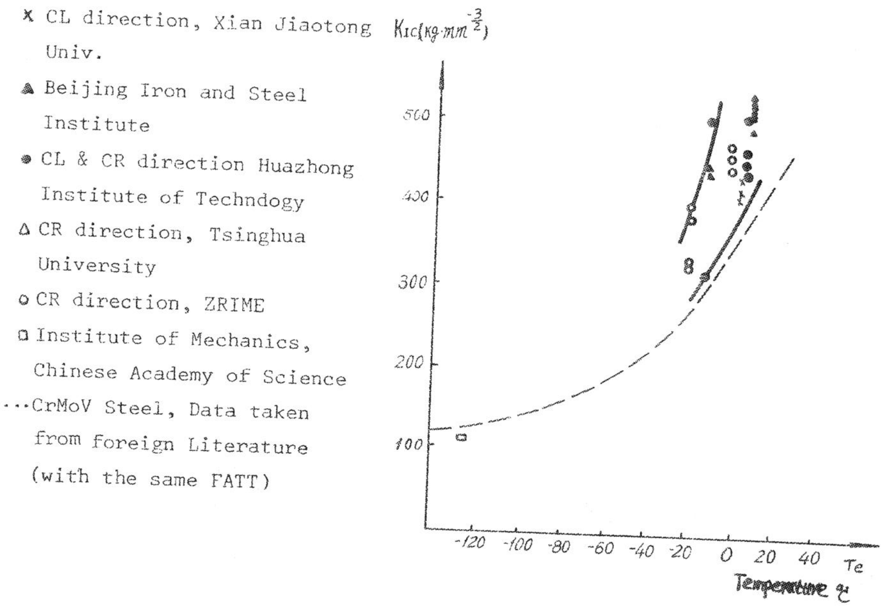

Fig. 2 K_{Ic} vs temperature

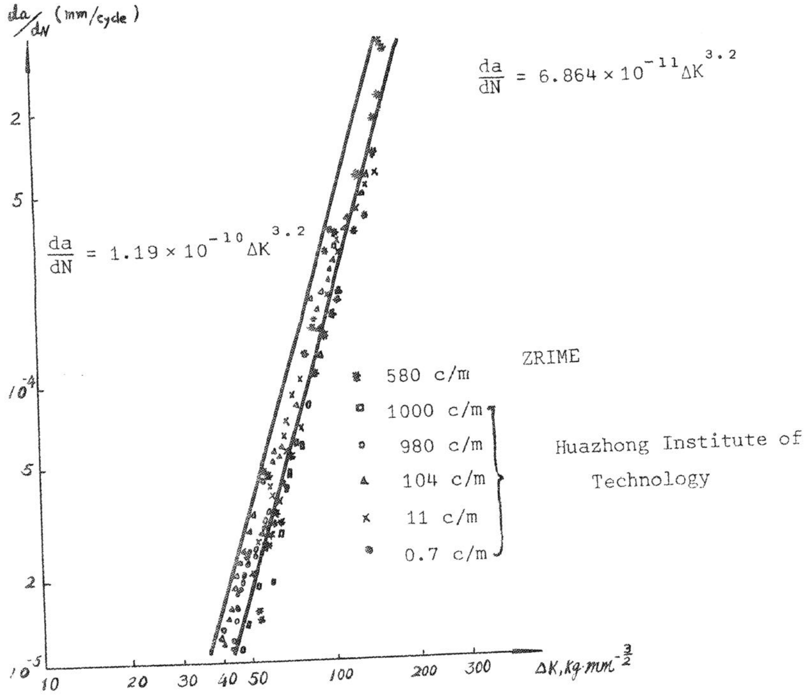

Fig. 3 Scatter band of $\frac{da}{dN}$ — K

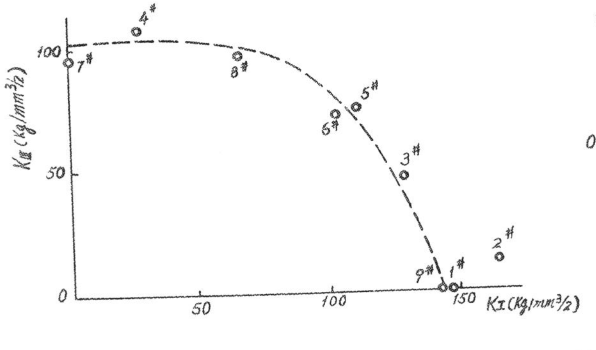

Fig. 4 Experimental Correlation of K_I — K_{III}

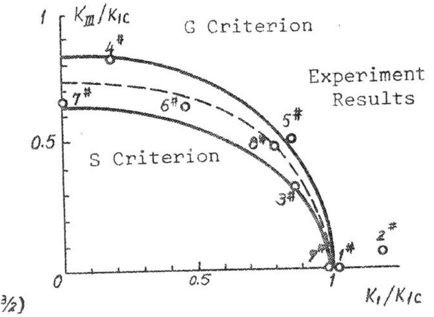

Fig. 5 Experimental results versus theoretical criterion

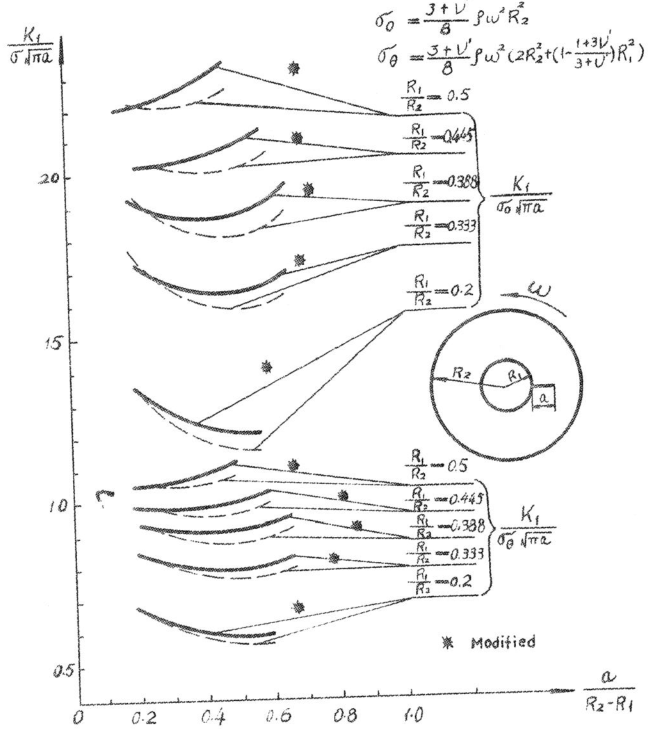

Fig. 6 Calculated stress intensity factor versus crack length

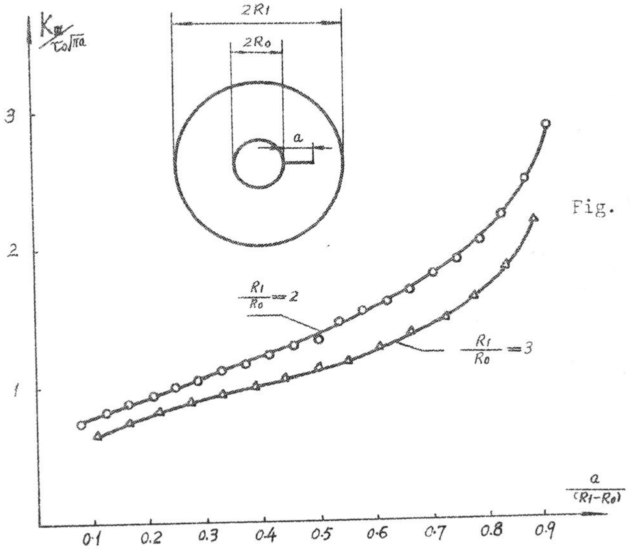

Fig. 7 Curves calculated from average values by Wilson-method

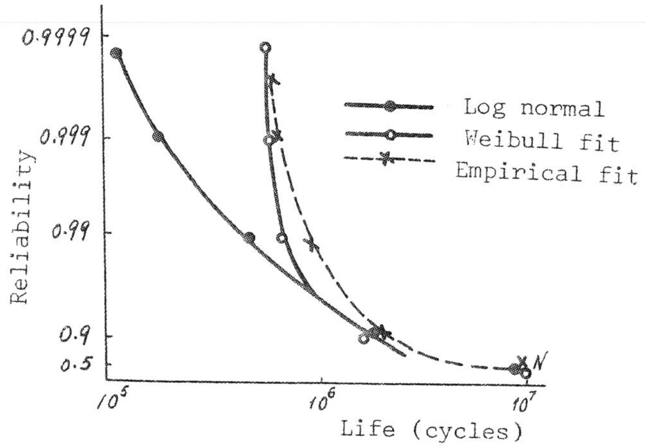

Fig. 8 Life vs. reliability

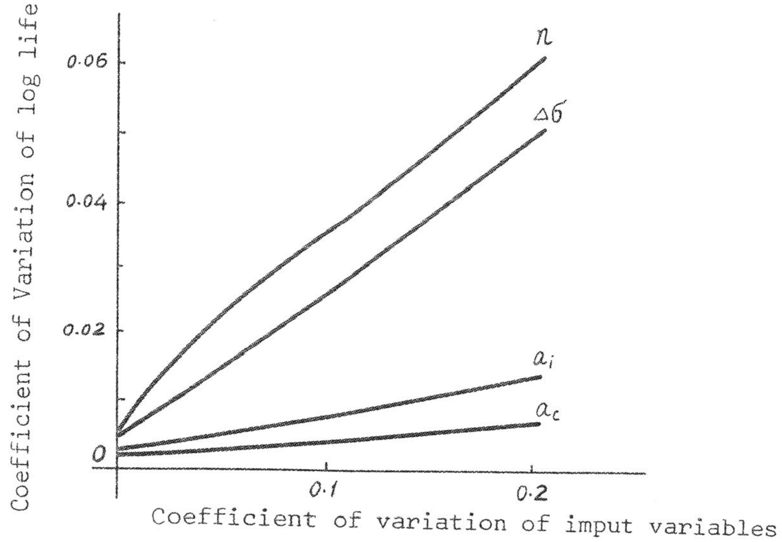

Fig. 9 Effect of imput variables on the life scatter

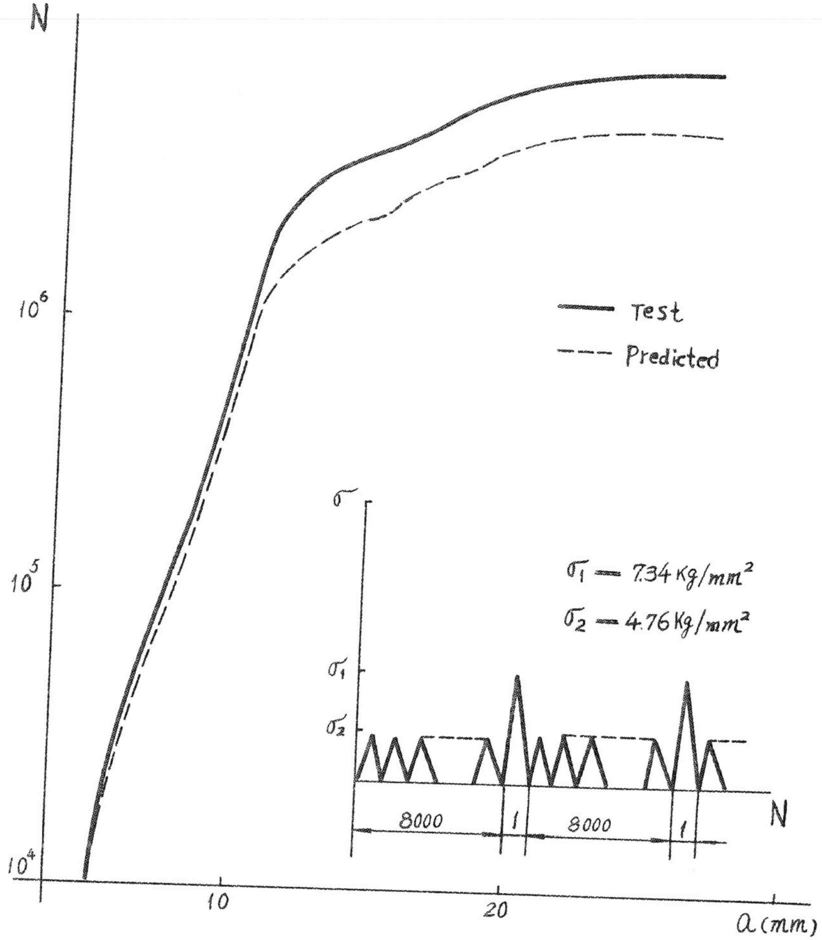

Fig. 10 a - N Curve