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Review of Aeronautical Fatigue Investigations in Japan During the Last Years

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1. INTRODUCTION

National Aeronautical Laboratory, redesignated as National Aerospace Laboratory in 1963, was established in 1955, and it coincides just after the accidents of D.H. "Comet I" had happened. Since then, it was recognized that the research on fatigue of aeroplane structures was one of the most important and urgent problems in developing new types of aeroplanes.

The representative aeroplanes developed in Japan during the last two decades include the followings:

Fuji T-1 intermediate jet trainer
NAMC YS-11 twin turboprop transport
Mitsubishi MU-2 twin turboprop utility transport
Fuji FA-200 "Aero Subaru" light aeroplane
Kawasaki C-1 twin turbofan medium range military transport
Shinmeiwa PS-1 four turboprop STOL flying boat
Mitsubishi T-2 supersonic jet trainer

The greater part of the structural component fatigue tests of these aeroplanes were carried out by employing the fatigue testing facilities installed in NAL.

The full scale fatigue tests were conducted at NAL and the related manufacturing companies for civil aeroplanes, but for military aeroplanes the tests were conducted at the Third Research Center, the Technical Research and Development Institute, Japan Defence Agency.

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In Japan, the research on the fatigue strength of the structures and their components has been actively conducted in the field of mechanical engineering, such as cars and trains, and shipbuilding. But in aeronautical engineering, it has been limited and conducted mainly in NAL and in some universities.

This paper reviews the investigations on aeronautical fatigue tests in developing new types of aeroplanes and on some research on fatigue strength of aeroplane structural components and parts conducted in NAL, including some basic research on cumulative damage rule and stress analyses of cracks in universities.

2. BASIC RESEARCH ON FATIGUE PROPERTIES

Some basic research on fatigue properties of aluminum alloy were conducted in NAL and some theoretical study on cumulative damage has been executed in Tohoku University.

2.1 Statistical Research on Fatigue Life

(1) Scatter of Fatigue Life

2024-T4 aluminum alloy unnotched bar specimens were tested under rotating bending load at room temperature, and the data on scatter of fatigue life were obtained[1].

Fig. 1 shows the S-N curve, which was obtained by arranging the experimental results using least squares method. Fig. 2 indicates the relation between stress level and the calculated standard deviation of fatigue life, assuming the log-normal distribution.

The relation between the coefficients of variation and log-life is shown in Fig. 3, in which the test results of pulsating tension by SCHIJVE et al[2] are also presented.

Also, by the results of plain bending fatigue test on the sheet specimen of 2024-T4 and 7075-T6 with a center hole, and axial load fatigue test on unnotched bar specimen of 2024-T4 aluminum alloy[3],it was shown that in the former case, fatigue life decreases with the increase of the thickness under the same maximum stress in the repeated stress and the same stress ratio R (as shown in Fig. 4), and that in the latter case, the endurance strength for N cycles in term of maximum stress increase with the increase of R.

(2) Distribution Function of Fatigue Life

Unnotched and Notched 2024-T4 aluminum alloy sheet specimens were tested[4]. The S-N curve, where N is median fatigue life, is determined by the test results. Then, the equivalent stress of each specimen, which is considered to be the sum of the applied stress and estimated error, which includes all factors contributing the scatter of fatigue life, is calculated. It was found that the distribution of equivalent stress is almost a normal, and the values of coefficient of variation of the fatigue life obtained are more than five times as large as those of equivalent stress.

The followings are concluded by this investigation: In the range where the S-N curve on a semi-logarithmic plot is nearly straight, the distribution of fatigue life is considered to be a log-normal. But, in the lower stress range, as the applied stress decreases, the fatigue life deviates gradually from the log-normal distribution and its skewness is more pronounced (Fig. 5).

2.2 some New Rules on Cumulative Damage

(1) Two Stage Stochastic Process[5]

An approach to fatigue by random loadings has been developed in treating fatigue process as two stages successive stochastic process consisting of crack initiation stage and crack propagation stage.

A method was proposed to estimate fatigue life under random load, and the calculated result showed good agreement with an experiment under Rayleign random loadings, as shown in Table 1.

(2) Nonlinear Cumulative Damage Rule

Based on the probabilistic model in term of stochastic theory, cumulative damage rule for time-dependent fracture was developed[6].

The case in which crack propagation occupies most of total life as in fatigue of notched specimens and the probability of final fracture occurrence per cycle, which depends on the number of cycles N, was considered.

The following nonlinear cumulative damage rule was derived for fatigue fracture.

$$\sum \alpha_i (N_i / N_{fi})^{\gamma_i + 1} = 1 \qquad (2-1)$$

where

N_i = number of cycles of stress amplitude qi σ_i

N_{fi} = fatigue life under constant stress amplitude of $\sigma = \sigma_i$

γ_i = parameter which is dependent on material properties

α_i = parameter related to stress history

Replacing N by t in eq. (2-1), the following cumulative damage rule is obtained for creep.

$$\sum \beta_i (t_i / t_{fi})^{\eta_i + 1} = 1 \qquad (2-2)$$

where

t_i = time during which σ_i is applied in steady-state creep

t_{fi} = time to creep fracture under constant stress of $\sigma = \sigma_i$ in steady-state creep

η_i = parameter which is dependent on material properties

β_i = paremeter related to stress history

This rule may be also applicable to corrosion fatigue. And, these rules may be related to material properties through γ_i and η_i, and also may involve stress history effect through α_i and β_i.

Furthermore, a new approach was proposed to the problem of interaction of fatigue and creep[7]. That is, a constitutive equation for crack propagation was proposed which included both number of cycles N and time t based on the stochastic and kinetic theory approaches to time-dependent fracture.

Nonlinear life rule was derived as follows;

$$(N_f / N_{fF})^{\gamma^* - \lambda + 1} + (t_f / t_{fc})^{\eta^* - \zeta + 1} = 1 \qquad (2-3)$$

where

N_f = number of cycles of stress σ

N_{fF} = number of cycles to failure in time-dependent fatigue

t_f = time during which stress σ is applied in steady-state creep

t_{fc} = time to failure in creep

γ^*, η^* = parameters which are dependent on material properties

λ, ζ = exponents which are dependent on time and number of cycles respectively

2.3 Research on Fatigue Crack Propagation

(1) Improved Formula for Fatigue Crack Propagation[8]

Test was conducted on sheet specimens of such materials as aluminum alloys (2024-T4 and 7075-T6), heat-resistant alloys (17-7 PH stainless steel and Ti-6A1-4V titanium alloy), and 18-8 stainless steel.

By the results of the test, the following improved expression for fatigue crack propagation was proposed introducing the term of fatigue fracture thoughness k_{fc} into the expression which includes stress intensity factor and stress ratio R, and this expression has shown good agreement with the experimental results in reference 9.

$$d\ell/dn = C \cdot \Delta k^{\alpha} \cdot k^{\beta}_{max} / [(1-R)k_{fc} - \Delta k] \quad (2-4)$$

where Δk and k_{max} are the stress intensity factors based on stress range and maximum stress respectively, and C, α, β are constants shown in Table 2.

(2) Crack Arrestor[10]

Single notched sheet specimens of 2024-T3 aluminum alloy were tested to find out the most effective way to arrest the fatigue crack by the stop-hole.

It was concluded that;

a) The shorter the length of fatigue cracks at repairing, the more effective.

b) The radius of the stop-hole should be large enough to reduce sufficiently the stress concentration effect near the crack tip.

c) The distance between the front edge of the stop-hole and the tip of the fatigue crack should be short enough to leave the residual compression region around the crack tip.

(3) Crack Propagation of Stiffened Panel[11]

The fatigue crack propagation behavior of sheet specimens with riveted and/or bonded stiffners were also investigated.

The results show that the fatigue life of the sheet with the bonded stiffeners was considerably longer than that of the sheet with the riveted stiffeners. The calculated crack propagation rate for the sheet with the riveted stiffeners using the method proposed by C.C. POE, JR[12]. was in good agreement with this experimental result except in the vicinity of stiffener.

2.4 Some Results of Fatigue Test of CFRP (Carbon Fiber Reinforced Plastics)[13]

The experimental investigation on bending fatigue test of composite materials with carbon fiber reinforcement was carried out both at room temperature and at 120°C.

The test results show that the CFRP has considerably longer fatigue life than GFRP (grass fiber reinforced plastics), and that heat-resistant CFRP has high fatigue strength even at 120°C.

The S-N curves for two types of CFRP test specimens are shown in Fig. 6. In testing those materials, the fatigue testing machine was modified to avoid the overstress on the specimen at the start of the operation.

3. STRESS ANALYSIS OF CRACKS

It is well known that the fatigue crack propagation rate is expressed by a function of stress intensity factors and that the unstable fracture of the cracked material will occur when the values of those factors reach the critical value inherent to the material. Consequently, it is required to calculate the theoretical values of stress intensity factors.

The followings are the summaries of the analysis of two dimensional stress field with cracks by ISIDA and his coworkers.

3.1 Method of Laurent Expansion

ISIDA developed a method to calculate stress intensity factors for the infinite plate with arbitrary number of cracks and circular inclusions or voids at any position and orientation under arbitrary loading conditions.[14] The analyses are based on Laurent expansions of complex stress potentials where the expansion coefficients are determined from the boundary conditions. Fig. 7 shows a result of this investigation. The relaxation effect of side stiffeners to the stress field of a center crack in a strip subjected to tension is shown in Fig. 8.[15]

3.2 Collocation Method

ISIDA et al treated rectangular plate with a center crack under arbitrary symmetric loading,[16, 17, 18] and rotating disc containing an arbitrarily located crack.[19, 20] A collocation method is used to analyze the above-mentioned crack problems in a finite plate. Fig. 9 shows the example of results obtained by this method.

Furthermore, by treating an eccentric crack in a finite plate using a modified boundary conditions, the stress intensity factors corresponding to two collinear cracks in a finite plate, parallel cracks perpendicular to loading direction in a strip, periodic collinear cracks in a strip and various kinds of periodical cracks in an infinite plate are also derived by the same method.[21]

3.3 Other Methods

NISHITANI et al [22, 23] developed the body force method to analyze the crack problems based on the appropriate arrangement of body forces along the boundary segments. The intensity of the body force of each segment is determined by the boundary conditions. YOKOBORI et al[24] treated the crack problems using the stress field given by the arbitrary array of edge dislocations. By this method the interacting effects of adjacent cracks, which is difficult to analyze by other methods, were solved.

There are also many works by means of the finite element method. Among them, the hybrid method with analytical solution[25] gives the highly accurate results.

4. STUDY ON ACOUSTIC FATIGUE

The research on acoustic fatigue has been conducted in NAL using the acoustic fatigue test facility installed in 1973. Riveted panel specimens of 2024-T3 aluminum alloy were tested under acoustic loadings. By the test, data on the noise field characteristics at the test section of the test facility, the strain response of the panel, and the relation between the applied acoustic load spectrum and the acoustic fatigue life of panel were obtained.

On the other hand, an estimation of acoustic fatigue life of the riveted panel under acoustic loading was made by the results of conventional constant stress amplitude fatigue test by mechanical excitation, using the Miner's linear cumulative damage rule and Rayleigh distribution of peak value of stress response of panel. In Fig. 10, it is shown that the estimated acoustic fatigue life of the panel agrees well with the experimental results.

5. FULL SCALE FATIGUE TEST

Concerning the aeroplanes developed in Japan, a number of fatigue tests of the materials and structural parts and components were performed, and the full scale fatigue tests of YS-11 and C-1 were conducted. Also, the full scale fatigue test of T-2 is to be conducted between April and June 1975, and that of PS-1 will be performed from July 1975 succeedingly

In this section, the full scale fatigue tests of YS-11 and C-1 are stated briefly.

5.1 Full Scale Fatigue Test of YS-11 Twin-Turboprop Transport

For the proto type of YS-11, the full scale fatigue tests were conducted from Aug. 1962 to Mar. 1965 to guarantee the service life of 30,000 flight hours. The spectrum fatigue tests of the full scale wing and fuselage were performed separately, because the critical load spectrum was considered to be different from each other. The details of the fatigue tests are described in reference 26.

Furthermore, the spectrum fatigue test of the full scale wing, of which structure was required to be converted by the increase of 2.2 ton to the maximum take-off weight, was conducted again from July 1971 to June 1972. The programmed load spectrum of this test was decided in carefully considering[27] GAG (ground-air-ground) loads, steps of loads and block size.

The programmed load spectrum employed is shown in fig. 11. One block corresponds to 100 flight hours and the flight load sequence is the ascending-descending order. The GAG cycles of 10 batches of 10 cycles are inserted into one block. The minimum load in the block is the minimum ground load obtained by considering the weight and taxiing load.

The main purpose of this fatigue test was to evaluate the fail safe characteristics of the structure. After the conventional fatigue test was finished, the additional fatigue test with saw-cut at stringers, panels and spars which were considered to be located in the critical area was continued and the fatigue damage regions were observed carefully during the test.

5.2 Full Scale Fatigue Test of C-1 Twin Turbofan Transport

There is a large downward-opening door at the rear end of cabin of C-1 transport which can be opened to the full width of cabin cross-section for cargo dropping. Models of the rear fuselage and the front fuselage were tested by only using the repeated internal air pressure before the fatigue test of the full scale aeroplane. The results were taken into redesigning the structural parts.

The fatigue test of the full scale C-1 transport aeroplane was conducted from May to Sept. in 1974 by random repeated loads corresponding to about 60,000 flights. The cabin was pressurized by air in each flight. The arrangement of 100 hydraulic actuators for external loads is shown in Fig. 12. The kinds of the external loads are shown in Table 3. The frequencies of the loads are decided according to the U.S. military specification.[28] The programmed load spectrum is designed by means of so called "flight by flight" with the random external loads and one cycle of the load spectrum is corresponding to 30,000 flights.

6. SCATTER FACTOR FOR FATIGUE LIFE OF CIVIL AEROPLANE STRUCTURE

The sample size of the full scale fatigue tests is useually less than two because of the restriction of time and expenditure. However, since the fatigue life essentially has large scatter, the scatter factor has to be introduced by employing statistical method in order to guarantee the safe life from the fatigue test results of such small sample size. The estimation of the safe life from few results of the full scale fatigue tests by the statistical method was made in the development of YS-11. Since then, by using the accumulated experimental data of fatigue tests, the revised scatter factor was proposed.[29] It is described in the following;

The scatter factor is defined as follows,

$$S_f = N / N_p \qquad (6-1)$$

where

S_f = scatter factor to geometric mean value of fatigue lives

N = geometric mean value of fatigue lives

N_p = safe life

If the distribution function of fatigue life is assumed to be lognormal and the standard deviation of the distribution is assumed to be known from the past test data of similar structures which is made of the same kind of materials, the safe life is estimated with the confidence level $(1-\beta)$ and the specified probability of failure P as follows,

$$\log N_p = N-(k_p+k_\beta/\sqrt{n})\cdot\sigma \qquad (6-2)$$

where

k_p = standardized normal deviation corresponding to probability of failure P

$$P=\int_{-\infty}^{-k_p}(1/\sqrt{2\pi})\cdot\exp(-t^2/2)\cdot dt$$

k_β = standardized normal deviation corresponding to confidence level $(1-\beta)$

$$1-\beta=\int_{-\infty}^{-k_\beta}(1/\sqrt{2\pi})\cdot exp(-t^2/2)\cdot dt$$

n = sample size

σ = standard deviation of normal distribution

Substituting eq. (6-1) into eq. (6-2), the scatter factor is given by

$$\log S_f=(k_p+k_\beta/\sqrt{n})\cdot\sigma \qquad (6-3)$$

The scatter factors based on the probability of failure of 10^{-5}, which is a value stated in ICAO Airworthiness Technical Manual[30] and 90 percent confidence level are shown in Fig. 13.

In order to estimate the standard deviation σ, the results of fatigue tests of structural components, which relate to YS-11 and other transport type aeroplanes developed in Japan, are accumulated. The accumulated data consist of 62 groups and all specimens are riveted structure and the materials are 2024, 2014 and 7075 aluminum alloys. By these data, the standard deviation of log-normal distribution is estimated as 0.154.

The scatter factors obtained by using the standard deviation of 0.154 are shown in Table 4 in comparison with the scatter factors adopted in various countries.

7. ACKNOWLEDGEMENT

The authors greatly appreciate the cooperation and assistance of Prof. T. Yokobori, Tohoku Univ., Prof. M. Isida, Kyushu Univ. and colleagues in the Third Research Center, JDA, in preparing the manuscript of this review.

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Table 1. Comparison of the estimated life by Yokobori's method with the results of Head and Hook's random load fatigue test.

r.m.s. of stress (ksi)	mean life by Head's experiment (cycle)	estimated life by Yokobori's method for $\eta = 0.3$ (cycle)	estimated life by Miner's Rule (cycle)
11.22	2.74×10^6	2.94×10^6	6.9×10^6
12.25	1.21×10^6	1.27×10^6	3.4×10^6

Note: $\eta = \dfrac{\text{mean of crack initiation life}}{\text{mean of total life}}$

Table 2. Constants and fatigue fracture toughness in Eq. (2-4).

material	C	α	β	fatigue fracture toughness k_{fc} ($kg\ mm^{-\frac{3}{2}}$)
2024-T4	2.30×10^{-5}	3.76	-1.53	110.0
7075-T6	3.40×10^{-5}	3.47	-1.25	80.0
17-7 PH stainless steel	1.12×10^{-7}	3.20	-0.47	280.0
18-8 stainless steel	3.68×10^{-7}	2.68	0.0	208.5
Ti-6Al-4V	5.03×10^{-6}	2.92	-0.59	220.0

Table 3. The kinds of loading of full scale fatigue test of C-1 transport.

Loading case	Combination of loads
ground load before take off	vertical load(6)*, braking(2), turning(2), pivoting(1)
climb load	flaps down 20°, slats extended, level flight, cabin pressure increasing
flight load	flaps up, slats retracted, manoeuver(6), gust(7), cabin pressure maintained
descent load	flaps down 75°, slats extended, level flight, cabin pressure decreasing
landing load	vertical load(10), spin-up(3), spring-back(3)
ground load after landing	flaps up, slats retracted, vertical load(6), braking(2), turning(2), pivoting(1), thrust reversal

* Numbers in the parentheses indicate the number of steps of the respective load.

Table 4. Scatter factors in each country.

n	British Civil Airworthiness Requirements	Australian Civil	U.S.A.	Values* by this method (Japan)
1	6.0	7.50		7.2
2		5.70	2	6.3
3	4.5	5.17	to	5.9
4		4.90	4	5.7
5		4.75		5.6
6	3.5	4.62		5.5

* scatter factors obtained by this method;
$1-\beta=0.90$ ($k_\beta=1.28$) and $P=10^{-5}$ ($k_p=4.26$)

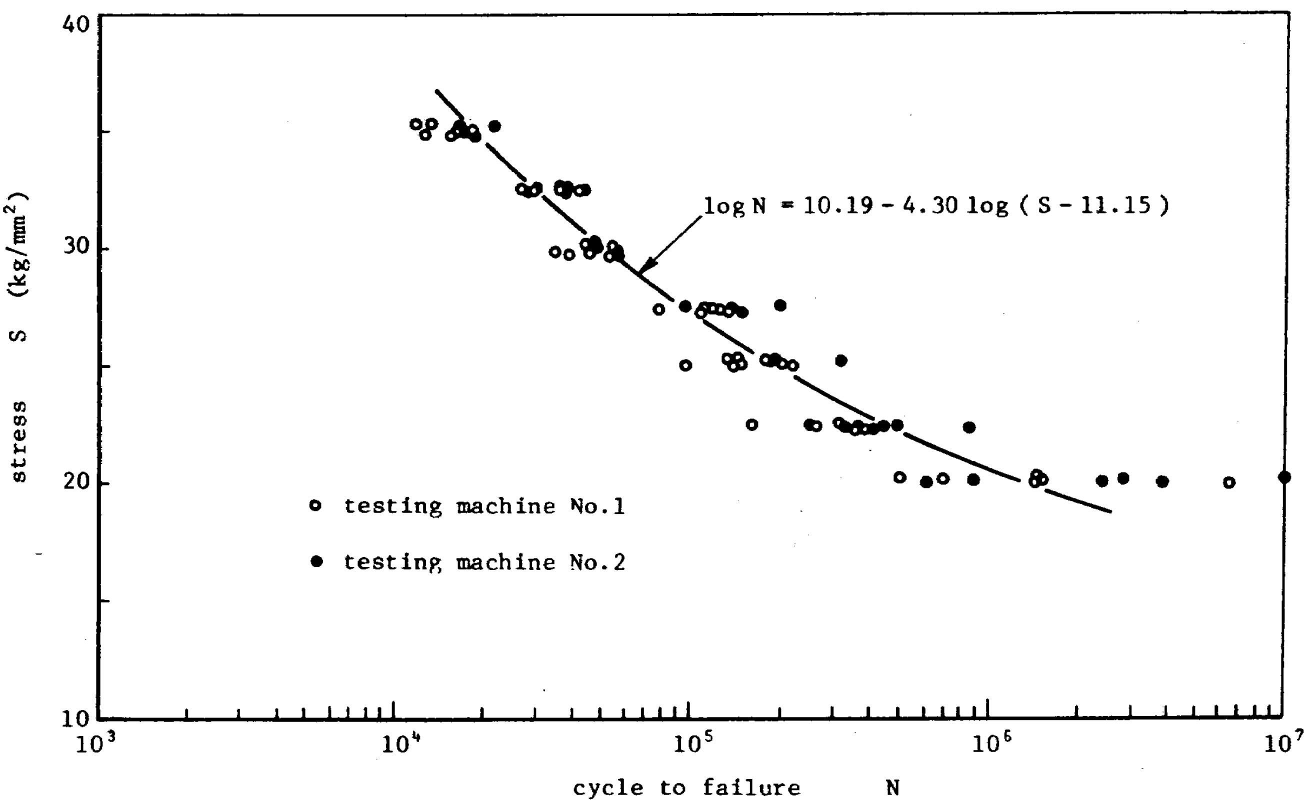


Fig. 1. S-N curve.

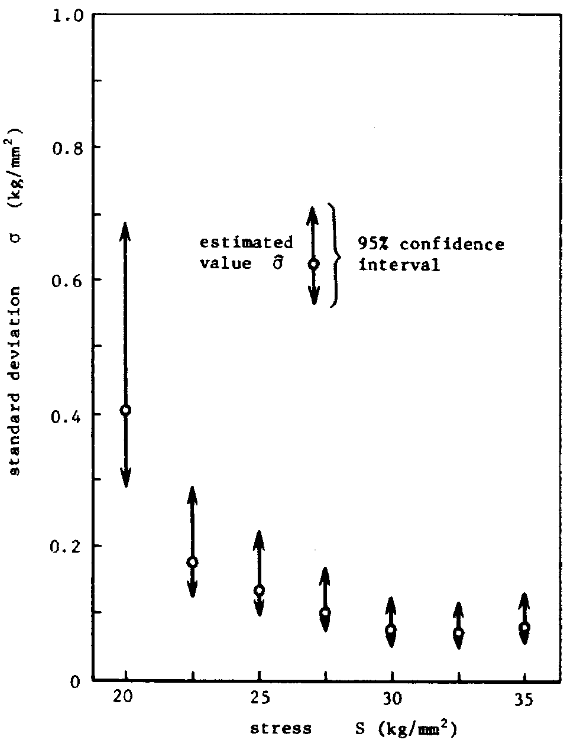


Fig. 2. Estimation of standard deviation of population.

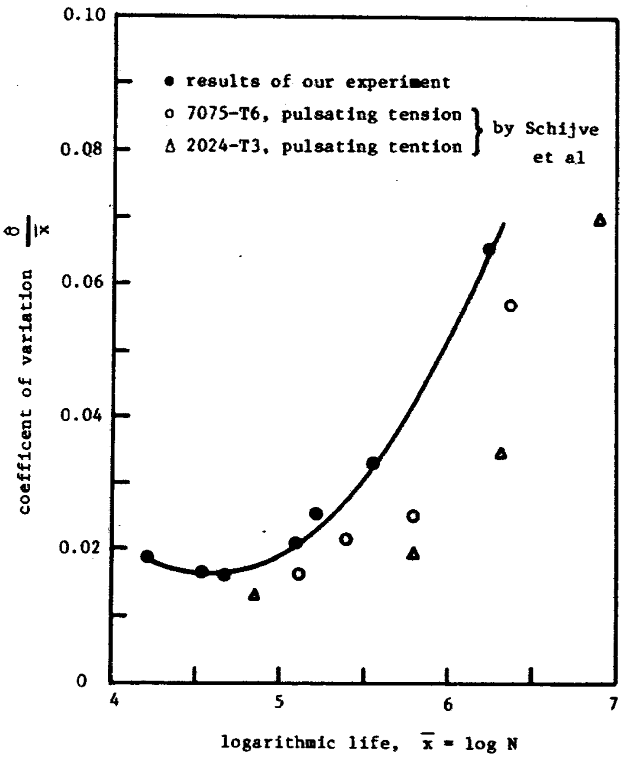


Fig. 3. Coefficient of variation.

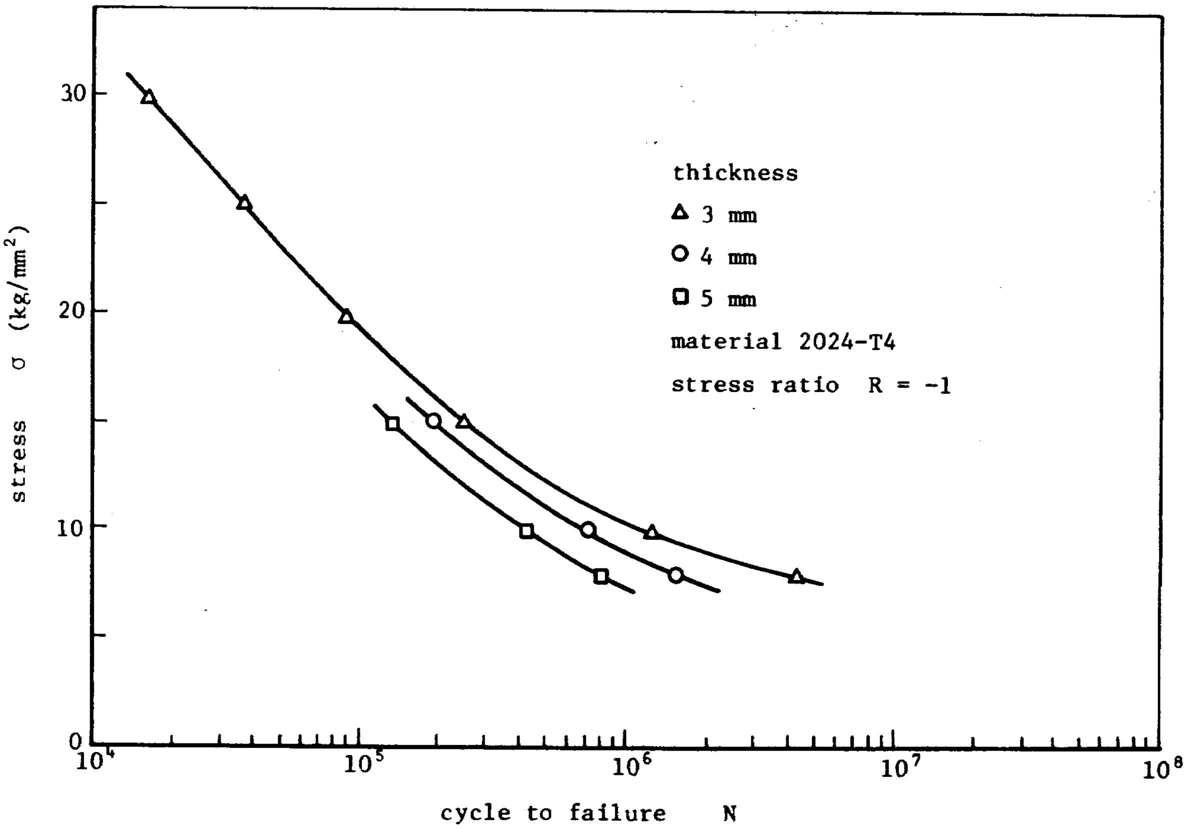


Fig. 4. Influence of specimen thickness.

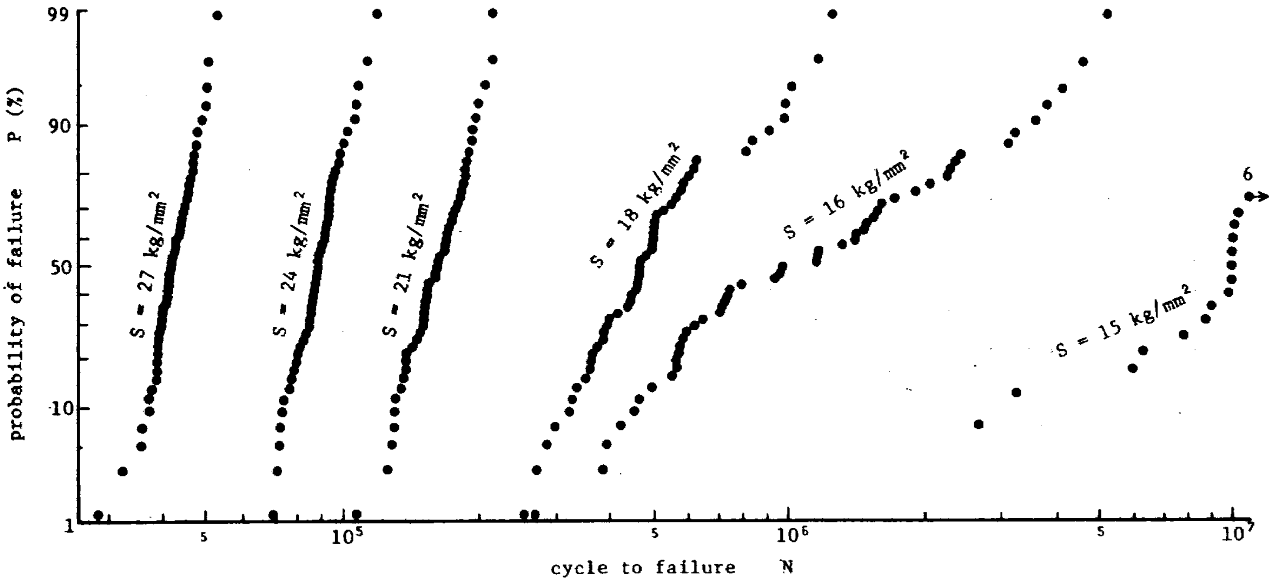


Fig. 5. Fatigue life distribution obtained by experiment.

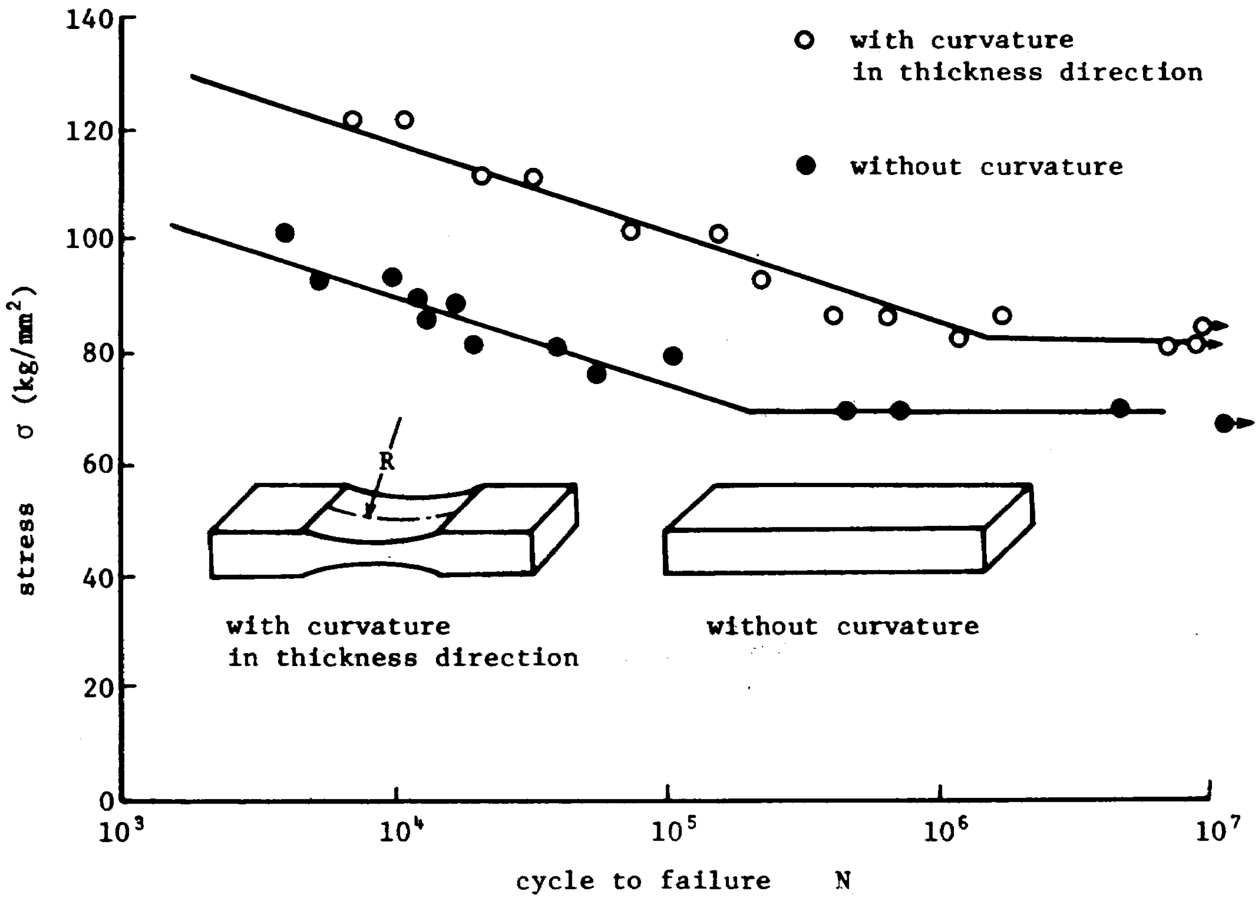


Fig. 6. S-N curve for CFRP.

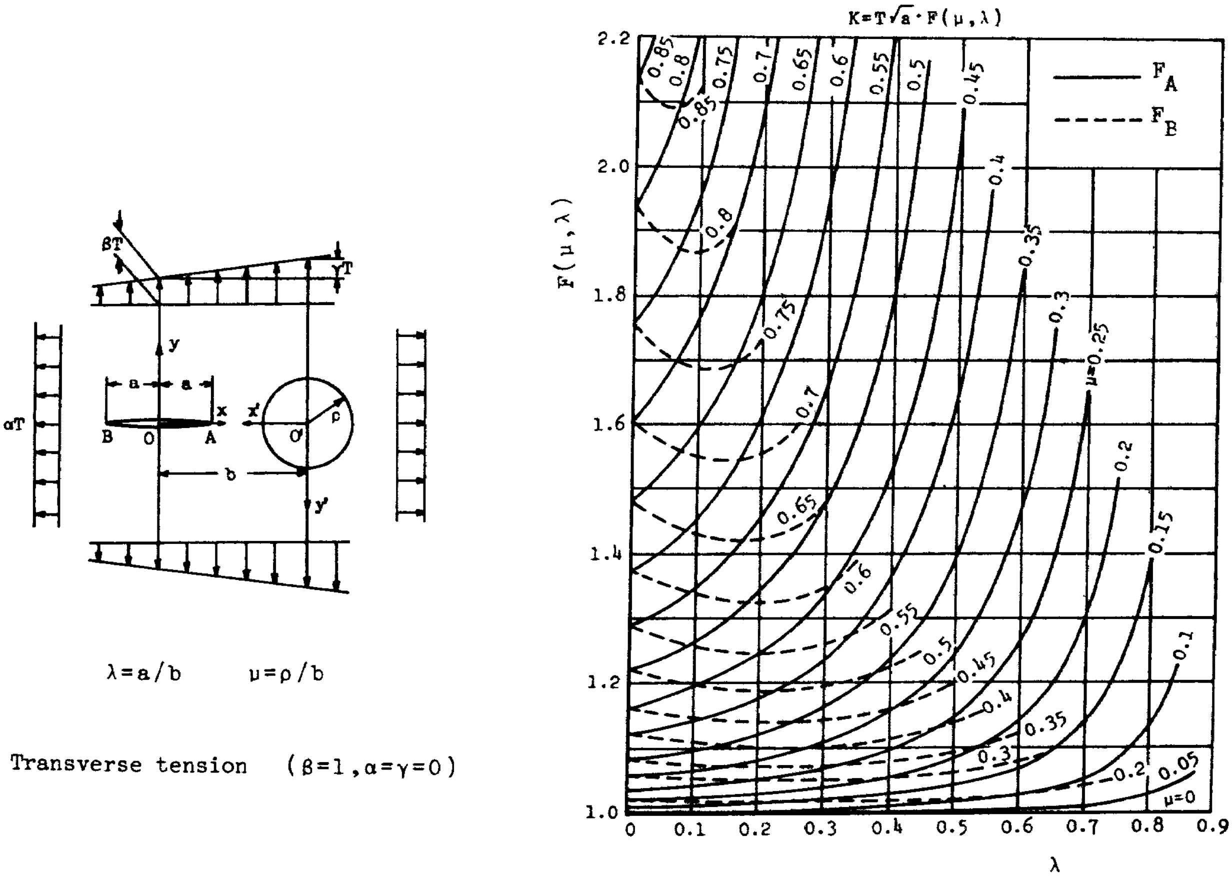


Fig. 7. Correction factor values for the crack approaching a hole.

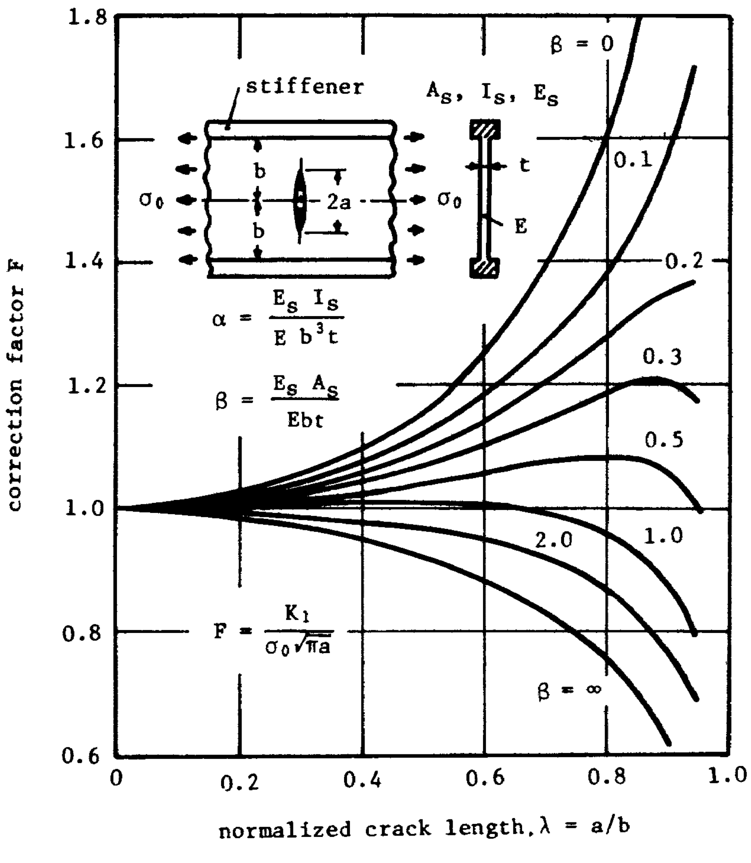


Fig. 8. Correction factor of K_I for $\alpha=0.05$

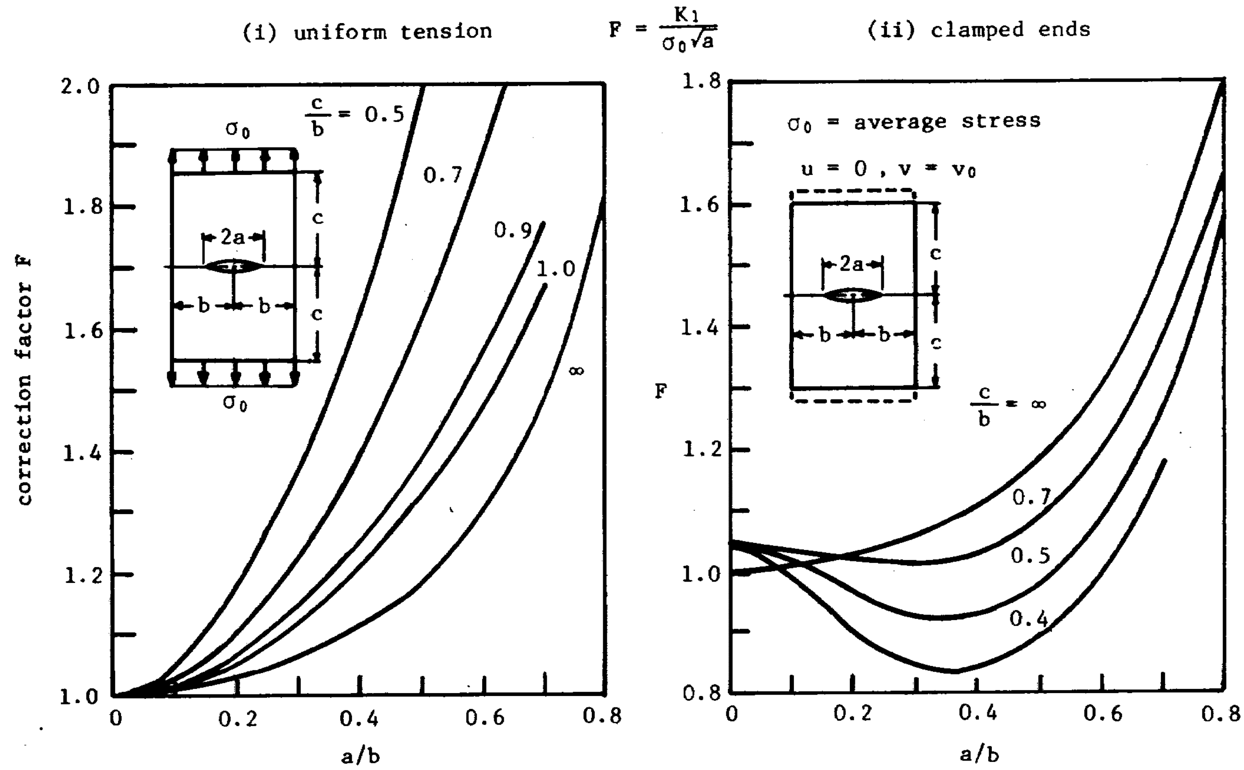


Fig. 9. Correction factors of K_I for uniform tension and clamped ends condition.

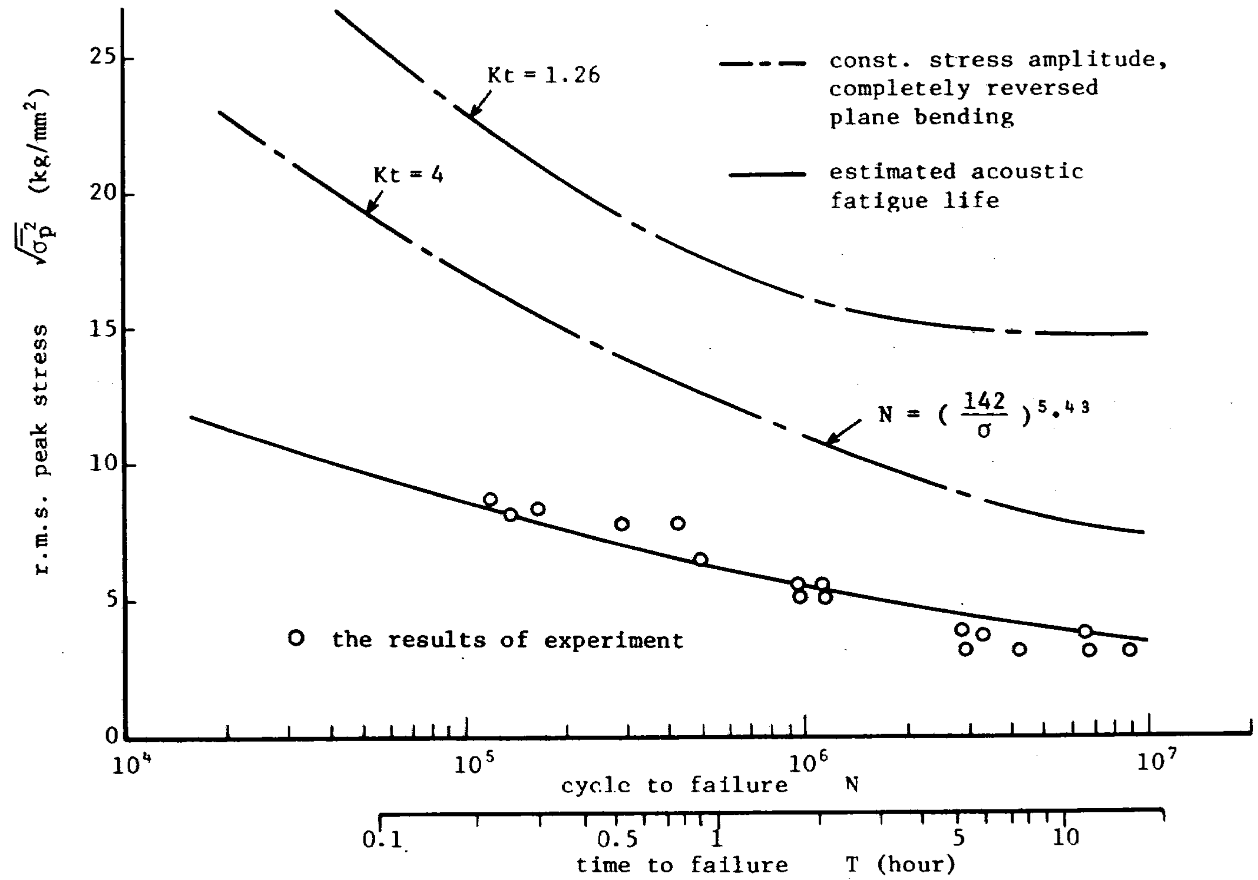


Fig. 10. Estimated S-N curve and experimental results.

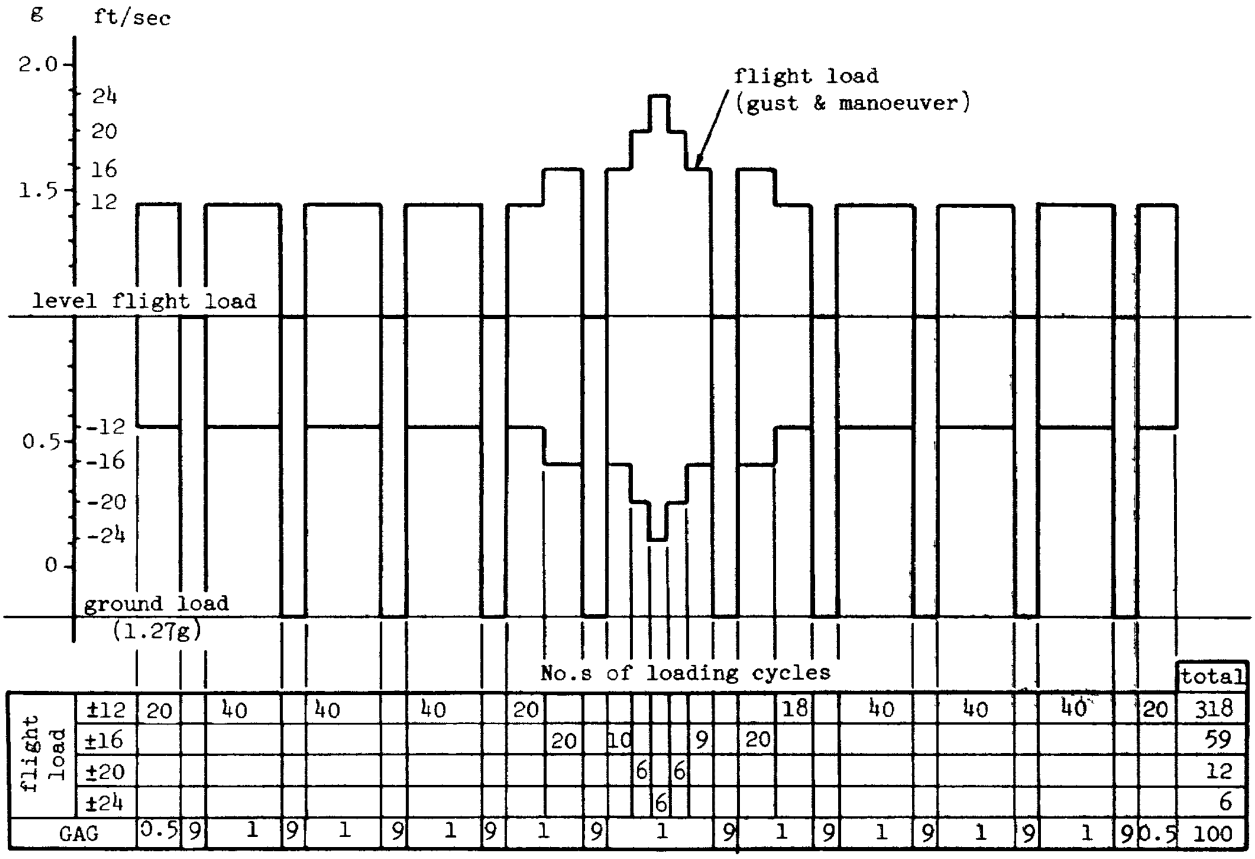
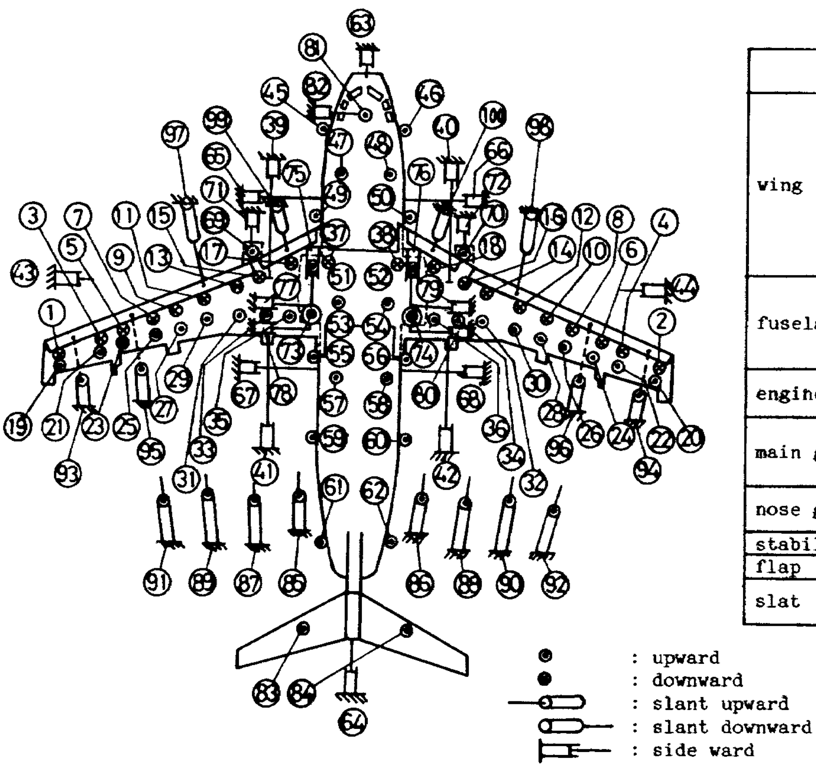


Fig. 11. Fatigue test spectrum of YS-11 full scale wing (for 100 flights).



		actuator No.	actuator capacity
wing	upper	1 - 14	10 ton
	(front spar)	15 - 18	20
	lower	19 - 32	10
	(rear spar)	33 - 36	20
	upward	37 38	20
	forward	39 40	20
	rearward	41 42	20
	sideward	43 44	20
fuselage	lower	45 - 62	20
	forward	63	20
	rearward	64	20
	sideward	65 - 68	20
engine	downward	69 70	20
	forward	71 72	20
main gear	upward	73 74	40
	forward	75 76	40
	sideward	77 - 80	20
nose gear	upward	81	20
	sideward	82	20
stabilizer	upward	83 84	20
flap	upward	85 - 92	10
slat	downward	93 - 96	10
	upward	97 -100	10

Fig. 12. Actuator arrangement of C-1 full scale fatigue test.

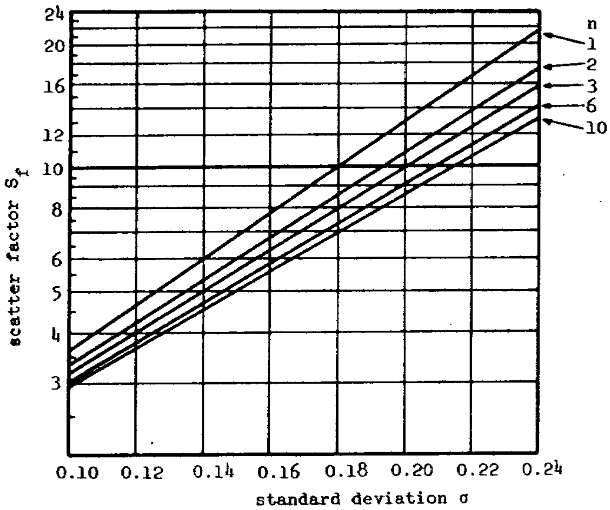


Fig. 13. Scatter factors (S_f) for $P=10^{-5}$ ($k_p=4.26$) and $1-\beta=0.90$ ($k_\beta=1.26$).

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