FATIGUE CRACK GROWTH AND CRACK CLOSURE OF STRUCTURAL MATERIALS UNDER RANDOM LOADINGS

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ABSTRACT

Fatigue crack growth tests were carried out under various programmed and pseudo-random loadings on a carbon steel, a high tensile strength steel and an alminum alloy, over a wide range of growth rate regime and crack closure behavior was investigated. Crack length and closure were measured by a mini-computer aided unloading elastic compliance method. The crack opening point was unchanged during one block of programmed load sequence and also during a period of pseudo-random loading. The crack opening stress intensity K_{op} was found to be controlled by the maximum stress intensity range-pair and its stress ratio, and furthermore, could be predicted from constant amplitude crack opening data. Cyclic counting methods were compared and the effective stress intensity range-pair counting was found pertinent to assessment of crack growth under irregular load histories. A prediction procedure was proposed for fatigue crack growth rates under stationary variable loadings.

KEYWORDS

Fatigue crack growth; crack closure; programmed loading; random loading; range-pair cycle counting method; prediction of crack growth rates.

INTRODUCTION

It is well known that there exists the load interaction effect on fatigue crack growth under complicated loadings, and fairly large number of experimental work has shown the crack growth acceleration by low-high load sequence and the retardation due to tensile overload or high-low load sequence(for example, Schijve, 1965; ASTM STP 595, 1976). Some models have also been proposed to estimate the crack growth retardation on the basis of the compressive residual stresses developed ahead of the crack tip(Wheeler, 1972). In recent years the crack closure concept proposed by Elber(1971) to explain the load history effect as well as the stress ratio effect,has been widely adopted to predict crack growth rates under varying loading conditions(for example, von Euw and others, 1972; ASTM STP 748, 1981), although the crack opening points have been estimated mostly by empirical formulae.

In earlier investigations (Kikukawa and others, 1976, 1977, 1981) a refined technique named as the unloading elastic compliance method was developed for measuring crack closure and crack length simultaneously, and performing repeated two- and three-step loading fatigue tests, some significant conclusions regarding crack closure and growth behavior were obtained: under variable amplitude loadings fatigue crack grows at low stress intensities below the threshold level, owing to the existence of high level load, and the growth rates can be predicted from constant amplitude test results by extrapolating the relation of crack growth rate dl/dn versus effective stress intensity range ΔK_{eff} far below the threshold level, as the modified-Miner rule in fatigue damage accumulation. In addition, the crack opening point is constant during one block of step loadings and the opening stress intensity K_{op} is governed by the high-level loading, being coincident with constant amplitude crack opening data for corresponding loading condition with the high-level load step.
However, since these conclusions were obtained from simple, stepwisely variable amplitude loading tests at a fixed stress ratio of R=0, it is necessary to solve the following two problems before utilizing the conclusions for the prediction of crack growth under more complicated variable load histories; one is to identify the cycle counting method most appropriate for fatigue crack growth rate estimation and the other is to evaluate effects of cycle-to-cycle variation of stress ratio on crack growth behavior.

In this study, first the repeated two-step loading tests with variable stress ratio were carried out to investigate effects of variation of stress ratio and subsequently cycle counting methods were compared on the test results of program loading with sinusoidal variation of mean stress. Further, pseudo-random loading tests having diffefnt power spectra were performed to derive a prediction procedure applicable to stationary variable loadings.

EXPERIMENTAL PROCEDURE

The materials used are a normalized 0.38% carbon steel S35C, a high tensile strength steel HT80 and a commercial aluminum alloy ZK141-T7. Their chemical composition and mechanical properties are shown in Tables 1 and 2.

Tests of the carbon steel S35C were performed using small, side-grooved SEN (Single Edge Notched) specimens on an electromagnetic type in-plane bending fatigue machine at 40 Hz and the steel HT80 and the alminum alloy ZK141-T7 were tested using side-grooved CCT (Center Cracked Tension) specimens on a closed loop servo-hydraulic testing system at 10 Hz. To avoid preloading effects on subsequent crack growth, K-increasing procedure was employed. Crack length and closure were measured cycle by cycle by a mini-computer aided unloading elastic compliance method (Kikukawa, 1980). Programmed and pseudo-random load histories were generated by a mini-computer.

TABLE 1 Chemical composition (%)

Steels	C	Si	Mn	P	S	Ni	Cr	Mo	Cu	V
S35C	0.38	0.25	0.72	0.01	0.015	0.02	0.13	-	0.04	-
HT80	0.12	0.33	0.83	0.011	0.009	0.81	0.44	0.40	0.25	0.04
Al.alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Zr	V
ZK141-T7	0.08	0.19	0.18	0.35	1.8	0.14	4.7	0.05	0.17	0.01

TABLE 2 Mechanical properties

Material	Yield point σ_Y (MPa)	Tensile strength σ_S (MPa)	Elongation δ (%)	Reduction of area ψ (%)	Fracture ductility ε_f (%)
S35C	373	612	23.7	58.5	88.0
HT80	766*	814	24.0	67.8	113.3
ZK141-T7	294*	370	18.3	47.2	63.9

* 0.2% proof stress, $\varepsilon = \ln\frac{1}{1-\psi}$

CRACK GROWTH BEHAVIOR UNDER REPEATED TWO-STEP LOADING TESTS WITH VARIABLE STRESS RATIO

In order to investigate effects of stress ratio, three series of two-step loading tests were carried out on the carbon steel S35C.

Experiment I As shown in the insert of Fig. 1, here the amplitude of the low-level load step ΔK_L was varied, keeping its maximum stress intensity K_{Lmax} same as that of the high-level load K_{Hmax}, where the amplitude and stress ratio of the high-level load were kept constant at ΔK_H =15.5 MPa$\sqrt{m}$ and R_H=0. Examples of load-differential displacement hysteresis loops sampled through one block of two-step loading specified above are illustrated in Fig. 1. The crack opening points indicated by the small bars on the hysteresis loops are found constant and below K_{Lmin} so that crack opens completely over ΔK_L. Similar trend was observed for all of ΔK_L values tested. The crack opening stress intensity K_{op} at the high-level load cycles was plotted against K_{Hmax} in Fig. 2 where the small solid marks denote constant amplitude crack opening data for R=0. K_{op} is hardly affected by ΔK_L, being almost coincident with constant amplitude data. This indicates that the crack closure behavior during repeated two-step loading of this kind is controlled by the high-levelload.

In Fig. 3, against ΔK_L and effective stress intensity range for low-level load ΔK_{Leff} which were identical in this case was plotted the crack growth rate of low-level load cycle $(dl/dn)_L^*$ calculated by the following equation assuming linear accumulation of crack growth,

$$(dl/dn)_L^* = [(dl/dn)_{HL} \times (N_H + N_L) - (dl/dn)_{\Delta K_{Heff}} \times N_H]/N_L \qquad (1)$$

where $(dl/dn)_{HL}$ is observed average growth rate during two-step loading, $(dl/dn)_{\Delta K_{Heff}}$ is the growth rate corresponding to the value of ΔK_{Heff} in constant amplitude growth rate data, and N_H and N_L are the numbers of cycles in each step perblock, respectively. Quantitative verification of Eq.(1) has been made through fractographical studies in the previous investigation

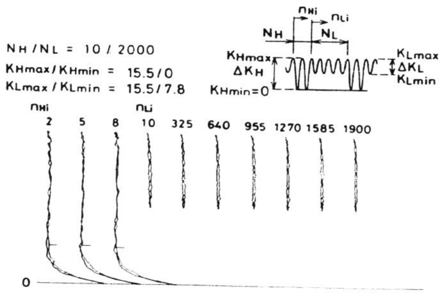


Fig. 1 Crack opening points during one block of repeated two-step loading

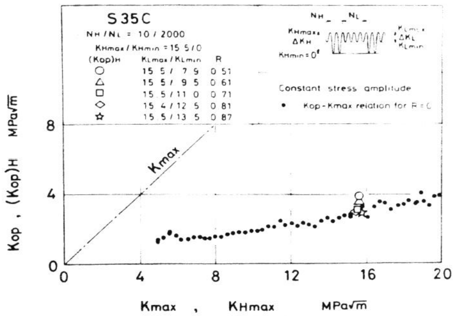


Fig. 2 K_{op} values when ΔK_L was varied [illegible]

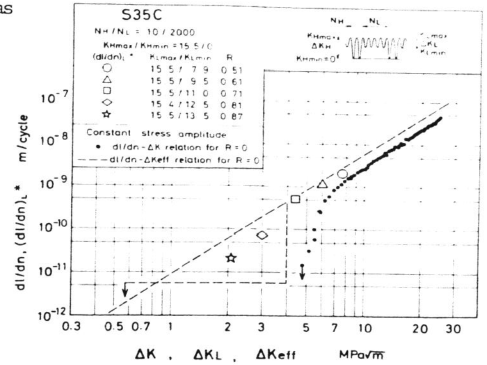


Fig. 3 $(dl/dn)_L^*$ - ΔK_{Leff} relation for low-level load cycles when ΔK_L was varied

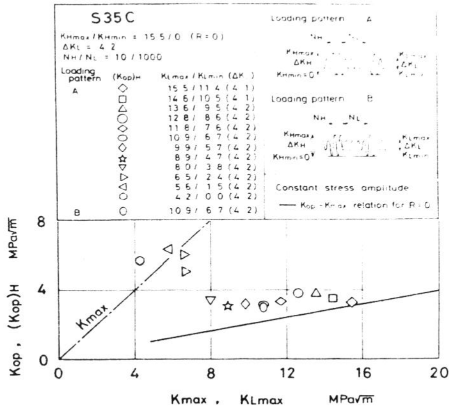


Fig. 4 Variation of K_{op} with K_{max}

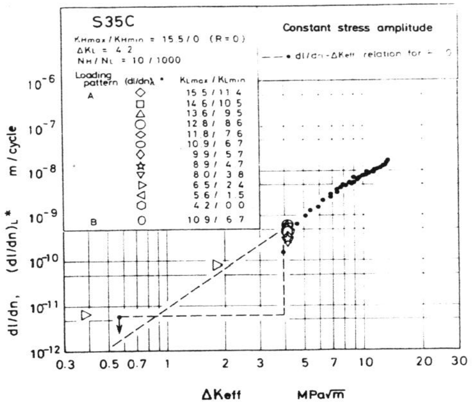


Fig. 5 $(dl/dn)_L^* - \Delta K_{Leff}$ relation when R_L was varied

(Kikukawa and others, 1981). The growth rate $(dl/dn)_L^*$ in terms of ΔK is faster compared with constant amplitude data denoted by small solid circles, whereas the $(dl/dn)_L^*$ versus ΔK_{Leff} plots agree well with the constant amplitude relation of dl/dn versus ΔK_{eff} extrapolated far below the threshold level.

Experiment II In this experiment the stress ratio of low-level load R_L was varied, keeping low-level amplitude ΔK_L constant at 4.2 MPa$\sqrt{m}$. The high-level loading conditions were identical with the previous case. K_{op} in this case is plotted against K_{Lmax} in Fig. 4. Except for extremly low K_{Lmax} approaching the threshold level, the K_{op} values are coincident with constant amplitude crack opening for the high level load step. $(dl/dn)_L^*$ was estimated via Eq. (1) and plotted against ΔK_{Leff} in Fig. 5. Similar to the previous case, the data fall on the extrapolated constant amplitude relation.

Experiment III The stress ratio of high-level load step R_H was fixed at other value than zero. As in Experiment II, the stress ratio of low-level load step R_L was varied, keeping ΔK_L constant. Figure 6 shows an example of crack opening behavior during one block of two-step loading for $R_H = 0.3$. The opening point is found unchanged throughout one block load cycles. Crack opening

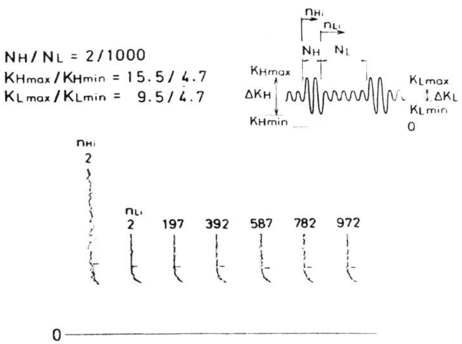


Fig. 6 Crack opening behavior during one block for $R_H = 0.3$

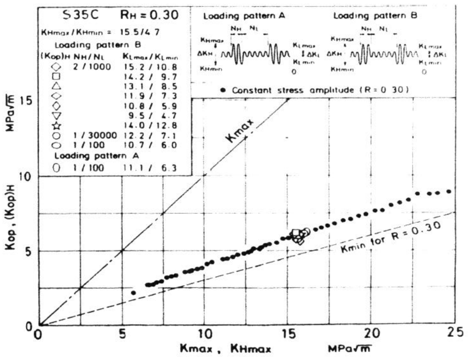


Fig. 7 K_{op} values for $R_H = 0.3$

stress intensity and growth rate data are shown in Figs. 7 and 8. Similar behaviors described in the above cases can be observed. Tests were also carried out for $R_H = -1.1$ and there could not be found any different behavior to be pointed out.

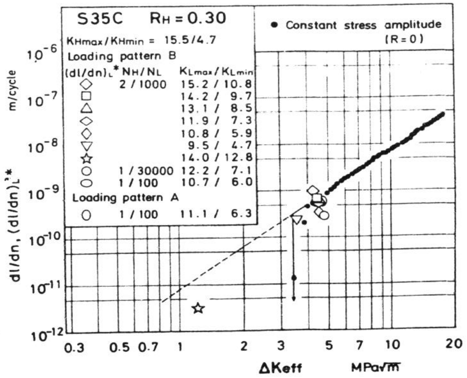


Fig. 8 $(dl/dn)_L^* - \Delta K_{Leff}$ relation for $R_H = 0.3$

It can be concluded from the experimental results hitherto described that even if variation of stress ratio is involved in step loadings, the crack opening point is almost constant throughout all load cycles in one block and further, since the opening stress intensity K_{op} is controlled by the high-level load step, K_{op} can be predicted from constant amplitude crack opening result corresponding to the high-level load cycle. In addition, the crack growth rate in terms of effective stress intensity range ΔK_{eff} is not affected by variation of stress ratio and the growth rate can be estimated by utilizing the linear accumulation law based on constant amplitude growth rate data extrapolated to low growth rate regime.

CYCLE COUNTING METHOD

There have been proposed so far many cycle counting methods, particularly associated with fatigue damage accumulation (Schijve, 1965). However, which of counting methods is most appropriate for the prediction of fatigue crack growth under irregular load histories has not been established yet. As found in the previous section, since the effect of mean stress or stress ratio does not appear in the dl/dn versus ΔK_{eff} relation, here was made a comparison between effective stress intensity range and range-pair countings. Comparative crack growth tests were conducted on three materials for the load sequence as shown in Fig. 9 which was expected to bring significant differences between the two counting methods. The test results were expressed in the growth increment prediction ratio λ defined by $\Delta l/\Delta l^*$ where Δl was observed increment and Δl^* was the predicted increment from constant amplitude growth rate data in terms of ΔK_{eff}, and listed in Table 3. The prediction ratio according to effective

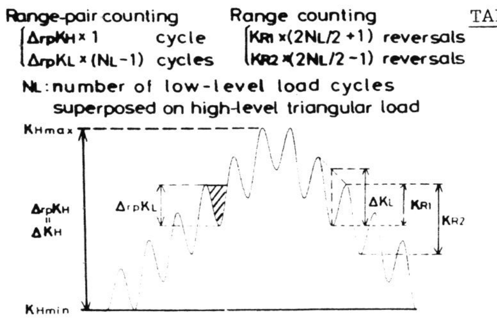


Fig. 9 Load sequence used for comparison of cycle counting methods

TABLE 3 Comparison of counting methods

Material	ΔK_H	ΔK_L	N_L	λ_{range}	$\lambda_{range-pair}$
S35C	15.5	4.3	10	1.88	1.13
	15.5	4.3	24	1.78	1.13
HT80	41.6	3.5	12	7.64	0.99
	41.6	3.4	26	8.39	0.90
	41.6	3.5	48	6.75	0.93
	41.6	3.5	130	4.10	0.87
	41.6	10.7	10	2.58	1.07
	41.6	9.8	22	2.58	1.09
	41.6	10.5	45	1.99	1.12
	41.6	10.1	110	1.45	1.04
ZK141 -T7	13.0	1.3	24	2.47	0.96
	18.9	3.7	24	1.94	1.29
	18.9	2.5	24	1.90	0.95
	18.9	1.9	24	2.93	1.08
	18.9	1.2	24	3.31	1.07
	18.9	1.9	100	1.47	0.88

stress intensity range λ_{range} varies from 1.45 to 8.39 depending on loading conditions, showing that the range counting method underestimates fatigue crack growth to lead to unconservative predictions, whereas the ratio based on the effective stress intensity range-pair $\lambda_{range\text{-}pair}$ is almost unity for all materials and loading conditions investigated, indicating that the effective stress intensity range-pair counting should be employed for the prediction of crack growth under complicated load histories.

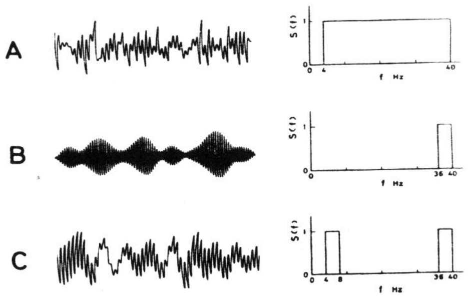


Fig. 10 Random load sequence

CRACK GROWTH BEHAVIOR UNDER RANDOM SPECTRUM LOADING TESTS

Three kinds of pseudo-random sequences having different power spectrum as shown in Fig. 10 were generated up to 1000 peaks by a mini-computer and tests were performed by repeatedly applying each random load sequence. The stress ratio of the maximum range-pair involved among the random sequence $R(\Delta rpK)max$ was kept zero for S35C and HT80. ZK141-T7 was tested for $R(\Delta rpK)max$ of 0 and 0.3. Fig. 11 shows a series of load-differential displacement hysteresis loops measured on ZK141- T7 through one block of random sequence C. The crack opening point is found unchanged during one block random load cycles, as in the repeated two-step loading tests on S35C. The crack opening stress intensity K_{op} was plotted against the maximum stress intensity $(K)_{max}$ included in the random load sequence, in Figs. 12(a), (b) and (c). The crack opening stress intensities under random loadings agree well with constant amplitude test results for all materials, irrespective of

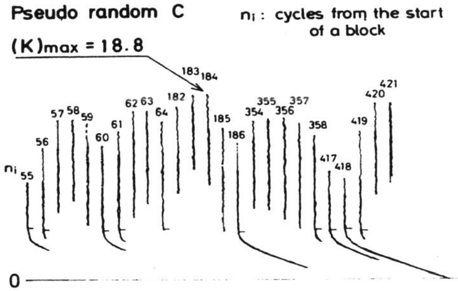
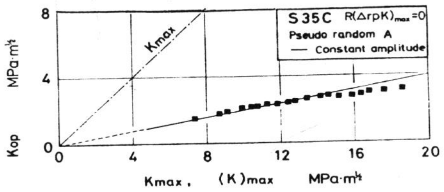
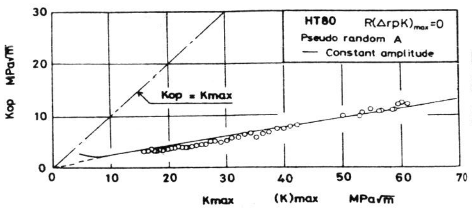


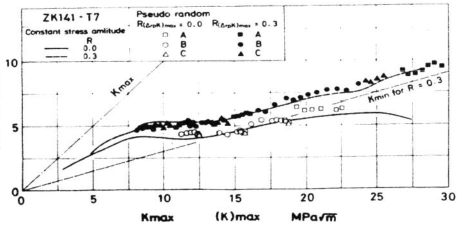
Fig. 11 Crack opening behavior during one block of random loading



(a) S35C



(b) HT80



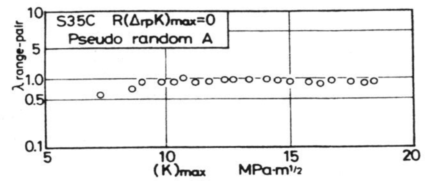
(c) ZK141-T7

Fig. 12 K_{op} under pseudo-random loadings

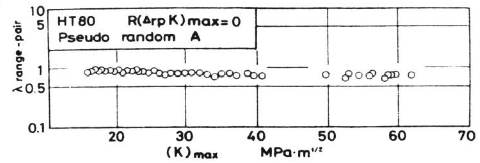
power spectrum. This indicates that the crack opening point under random loadings is controlled by the maximum stress intensity range-pair and its stress ratio. The crack growth results were evaluated in the growth increment prediction ratio in terms of effective stress intensity range-pair $\lambda_{range\text{-}pair}$ and shown in Figs. 13(a), (b) and (c). $\lambda_{range\text{-}pair}$ is found nearly unity over the wide range of $(K)_{max}$ investigated, for all spectra and materials.

PREDICTION PROCEDURE FOR CRACK GROWTH RATE UNDER STATIONARY VARIABLE LOADINGS INCLUDING RANDOM LOADS

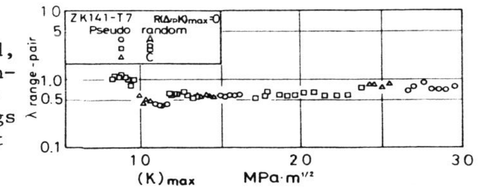
From the programmed and pseudo-random loading test results hitherto discribed, the crack growth behavior under stationary variable loadings can be characterized as follows; under variable loadings of periodicity, the crack opening point is unchanged during the period unless so long, and the crack opening stress intensity K_{op} is determined by the maximum stress intensity range-pair and its stress ratio, being coincident with the constant amplitude crack opening result for identical stress intensity range and stress ratio. On the other hand, the crack growth rate is controlled by the effective stress intensity range-pair $\Delta_{rp}K_{eff}$ rather than range and the relation of dl/dn versus $\Delta_{rp}K_{eff}$ for variable loadings agrees well with the constant amplitude relation of dl/dn versus ΔK_{eff} extrapolated below the threshold level as so-called modified-Miner rule in fatigue damage accumulation. Utilizing these characteristics, crack growth rates under stationary variable loadings may be predicted in the following manner:



(a) S35C



(b) HT80



(c) ZK141-T7

Fig. 13 $\lambda_{range\text{-}pair}$ for pseudo-random loadings

1. Construct a frequency distribution diagram in terms of stress intensity range-pair $\Delta_{rp}K$ and mean K_{mean} as shown in Fig. 14 from a K-history of moderate size, e.g., consisting of several thousand peaks.

2. Find the maximum stress intensity range-pair $(\Delta_{rp}K)_{max}$ and its stress ratio $R_{(\Delta rpK)max}$ in the diagram.

3. Assess the crack opening stress intensity K_{op} for the K-history concerned from constant amplitude crack opening result at identical values of ΔK and R with $(\Delta_{rp}K)_{max}$ and $R(\Delta rpK)_{max}$, respectively.

4. Locate the assessed K_{op} value on the ordinate of distribution diagram and draw two lines with the slopes of 1/2 and (-1/2) respectively originating from the location to delineate three regions I, II and III on the diagram as shown in Fig. 14 : In region I, $K_{op} \leq K_{min}$ and therefore $\Delta K_{eff} = \Delta_{rp}K$. In the region II where $K_{min} < K_{op} < K_{max}$ holds, effective stress intensity range can be calculated by the equation $\Delta K_{eff} = K_{mean} + \Delta_{rp}K/2 - K_{op}$. Cycles included in the region III where $K_{max} \leq K_{op}$, does not contribute to crack growth.

5. Utilizing ΔK_{eff} calculated above, crack growth increment or average

growth rate for the K-history concerned can be estimated from the constant amplitude relation of dl/dn versus ΔK_{eff} extrapolated below the threshold level. If constant amplitude growth rate data can be expressed over a wide range of growth rates by the equation

$$dl/dn = C(\Delta K_{eff})^m \qquad (2)$$

where C and m are material constants, crack growth increment Δl will be calculated as follows,

$$\Delta l = \sum_{i=1}^{k} C(\Delta_{rp}K_{eff})_i^m \cdot f(\Delta_{rp}K_{eff})_i \qquad (3)$$

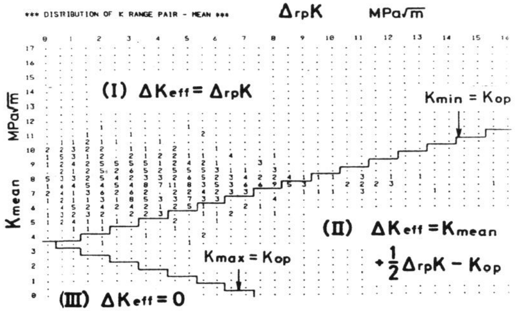


Fig. 14 Stress intensity range-pair - mean distribution diagram

where k is the number of levels of $\Delta_{rp}K_{eff}$ and $f(\Delta_{rp}K_{eff})$ is the frequency distribution of $\Delta_{rp}K_{eff}$.

CONCLUDING REMARKS

Through detailed studies on crack growth and closure under various programmed and pseudo-random loadings, characteristics of crack behavior under variable loadings were clarified and a simple prediction procedure of crack growth was proposed and proved to provide conservative estimation for stationary variable loadings of periodicity. However, to what extent of block or period size of stationary variable loading the characteristics of crack behavior observed in this study will be preserved or whether the prediction procedure proposed is applicable to non-stationary variable loadings is left to be solved. The two topics are now under investigation to be reported elsewhere.

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