Structural Eng. / Earthquake Eng. Vol. 4. No. 2, 371s-380s. October 1987
Japan Society of Civil Engineers (Proc. of JSCE No. 386/I-8)

FATIGUE CRACK GROWTH IN HIGHWAY BRIDGES

By Chitoshi MIKI, Jun MURAKOSI** and Masahiro SAKANO****

The fatigue crack growth behavior in the visinity of ΔK_{th} under computer simulated variable amplitude loads of highway bridge is studied experimentally. Fatigue crack growth under these load fluctuations is evaluated by using the linear damaged rule with paris law and ΔK_{th} including the influence of stress cycles below ΔK_{th} with adequate accuracy.
Keywords : fatigue crack growth, highway bridge, variable amplitude loads

1. INTRODUCTION

Fatigue damage at various parts of steel highway bridges has recently become conspicuous[1)~4)]. It has been considered in the past that there was little possibility of fatigue damage to highway bridges occurring in Japan, and in designing, except for cases of orthotropic steel decks, safety against fatigue had not been checked[5)]. However, when the conditions of traffic loads in recent years is considered, it is felt necessary for thorough attention to be paid to fatigue in future design and in maintenance and care of existing highway bridges.

Fatigue cracks in bridge members are formed at parts of acute stress concentration such as toes of fillet welds, and from defects in welding such as lack of fusion or slag inclusion Accordingly, for evaluation of fatigue strength and service life of bridge members, the use of a so-called fracture mechanics concept employing the relationship of the fatigue crack growth rate (da/dN) of the material and the stress intensity factor range (ΔK) will be effective. In such case, since various types of vehicles with various weights travel on the bridge in irregular order and at irregular intervals, the variations in stresses produced at the various parts of the bridge are extremely complex. Consequently, it is of great importance to investigate the fatigue crack growth properties under such variable stresses for performing fatigue life analyses using the fracture mechanics.

There are many studies that have been made in the past regarding fatigue crack growth under variable

* Member of JSCE, Dr. Eng., Associate Professor, Department of Civil Engineering, Tokyo Institute of Technology (O-okayama, Meguro-Ku, Tokyo)
** Member of JSCE, M. Eng., Graduate Student, Tokyo Institute of Technology (present, Ministry of construction, Public Work Research Institute)
*** Member of JSCE, M. Eng., Research Associate, Department of Construction Engineering, Gunma University (Kiryu-shi, Gunma)

stresses, and in the region where the Paris law holds good under constant-amplitude stress fluctuations, it is indicated that a fatigue crack growth rate on average under variable-amplitude load fluctuations can be predicted by using an equivalent stress range deduced by the linear damage rule, or by using root-mean-square and root-mean-cube values which are close to the above[6)~11)]. However, for evaluation of the fatigue life of a bridge member, the fatigue crack propagation property in the vicinity of the fatigue crack growth threshold stress intensity factor range, ΔK_{th} is of importance. When the equivalent stress intensity factor range for variable-amplitude load fluctuations including numerous repetitions of small stress ranges where the values will be not more than ΔK_{th} in a constant-amplitude stress range is obtained, even though the value may be below ΔK_{th}, apparently, fatigue cracks will grow[12)~21)]. Under variable-amplitude load fluctuations, it will be a hypothesis on the conservative side to consider that ΔK_{th} will disappear or to ignore its existence. However, for an evaluation of fatigue life of good accuracy to be made, it is necessary to find how cycles of stress of which stress intensity factor is less than ΔK_{th} under constant stress will affect fatigue crack growth.

The fatigue crack growth behavior in the vicinity of the fatigue crack growth threshold is complex and many factors such as sequence of stresses and average stress will exert influences. Therefore, it is necessary for fatigue crack growth characteristics to be investigated in a stress condition as close as possible to the stress fluctuations produced in actual bridge members[22)~23)]. In this study, traffic load simulations were made with the array and weights of vehicles, and spacing between vehicles as random variables, and fatigue crack growth tests were conducted with stress variations produced in bridge members when the load sequence passes were directly made input signals, and particularly, the growth behavior in the vicinity of ΔK_{th} was studied.

2. STRESSES OCCURRING IN HIGHWAY BRIDGE MEMBERS AND STRESSES USED IN TESTS

An example of stress histories at the bottom flange when a truck travels across a plate girder bridge is illustrated in Fig. 1[24)]. In the United States, stress ranges are read from such records by the peak-to-peak method with the objective of evaluating fatigue damage. In this case, the difference between the maximum and minimum stresses resulting from passage of a single truck was the stress range. In effect, a single stress range was produced by a single truck, and the other components of stress fluctuations were not counted. The frequency distribution of the stress range determined in this manner was considered as agreeing well with Rayliegh distribution, and many subsequent fatigue tests or fatigue crack growth tests of welded joints and structural elements have employed Rayleigh distributions.

Recently, actual stress measurements on long-term bases have been going on at highway bridges of Japan also. In these cases, stress-time records are A-D transformed and cycle counts of stress ranges are performed by the rain flow method. Fig. 2 shows distribution curves on parts of the results of measurement made by the Ministry of Construction where the abscissa of the frequency distributions are divided by the maximum stress ranges, with furthermore, the total number of cycles as 10^6 times[25)]. The ordinates were made logarithmic. All of the distribution curves are of roughly the same shapes being slightly concave from straight lines. This means that the frequency distribution of stresses actually acting are more in lower stress ranges than exponential distriburtions, to indicate extremely one-sided shapes.

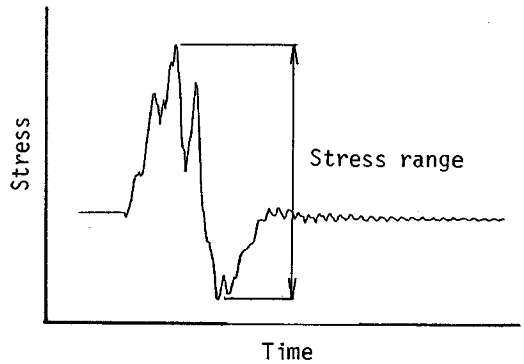

Fig. 1 Stress history at plate girder bottom flange when a truck travels across the bridge.

The results of stress fluctuation waveforms gener-

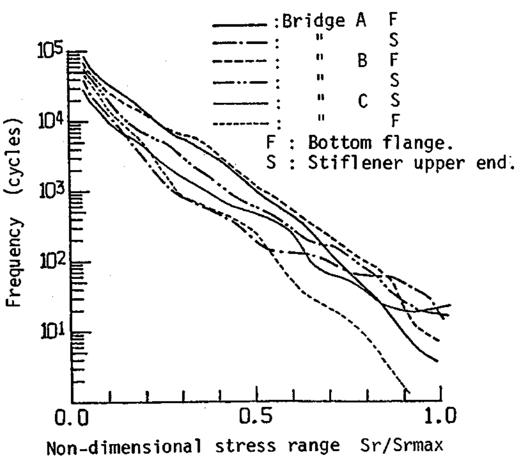

Fig. 2 Actual stress range frequency distributions in highway plate girder bridges.

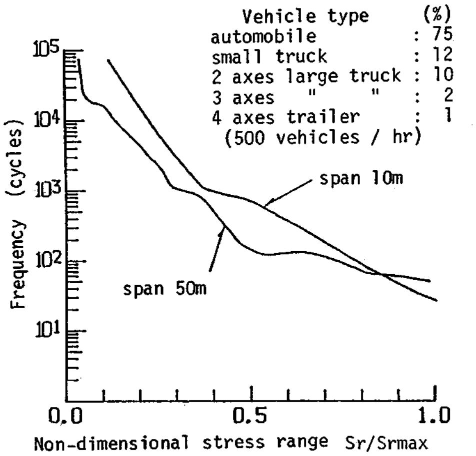

Fig. 3 Stress range frequency distributions generated by simulation.

ated by the computer simulation method[22] used in this study treated in the same manner are shown in Fig. 3. The frequency distribution shape of stress ranges of simulated wave is very close to the shape according to measurements, and it may be said that stress fluctuation waveforms by computer simulation adequately represent actual stress waveforms.

Fatigue crack growth tests were performed in this study with fluctuations in bending moment occurring at the middle of a 20-m span of simply supported girders when a column of vehicles obtained in simulations under the conditions given in Table 1 passes over as input waveforms. The number of vehicles producing bending moments in the simulation was 100 000. Fatigue crack growth experiments were conducted using waveforms deleting fluctuation waveform components below a certain proportion from the maximum values of fluctuation waveforms produced with the purposes of saving the time required for fatigue crack growth tests and to investigate the influences of low stress cycles. The method of deletion is shown in Fig. 4. Deletion of fluctuation waveforms on the low side in this manner corresponds to ignoring stress components produced when lightweight vehicles pass over the bridge singly.

Parts of the respective variable stress waveforms used in the tests and the results of cycle counting by the rain flow method are shown in Fig. 5. There are stress ranges lower than the designated stress deletion level counted in the frequency distribution diagram, but these are small stress fluctuation components superposed on high stresses, and comprise a characteristic of using test waveforms in the form of preserving actual stress variations as much as possible.

Table 1 Vehicle composition of simulation used for fatigue tests.

Vehicle type	Percentage
automobile	10
small truck	5
2 axes large truck	25
3 axes large truck	50
4 axes trailer	10

(1500 vehicles/h)

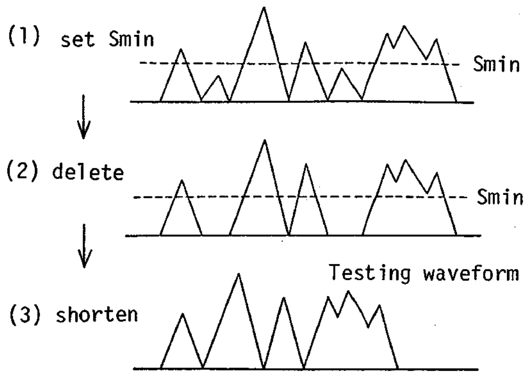

Fig. 4 Deletion of low stress cycles.

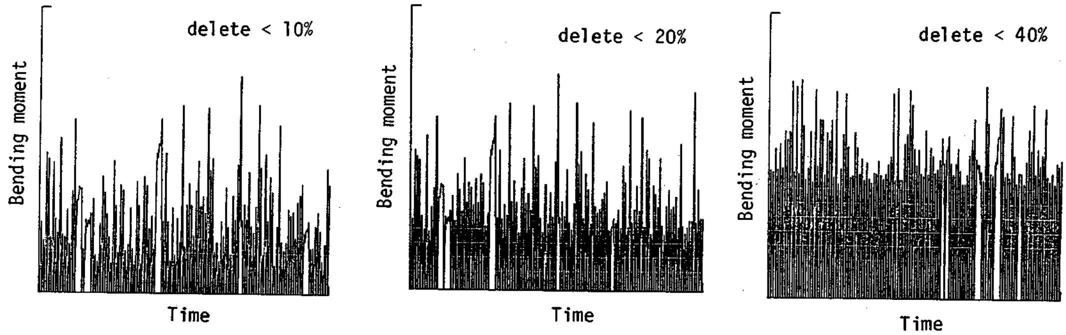

Fig. 5 (a) Variable stress waveforms used in the tests.

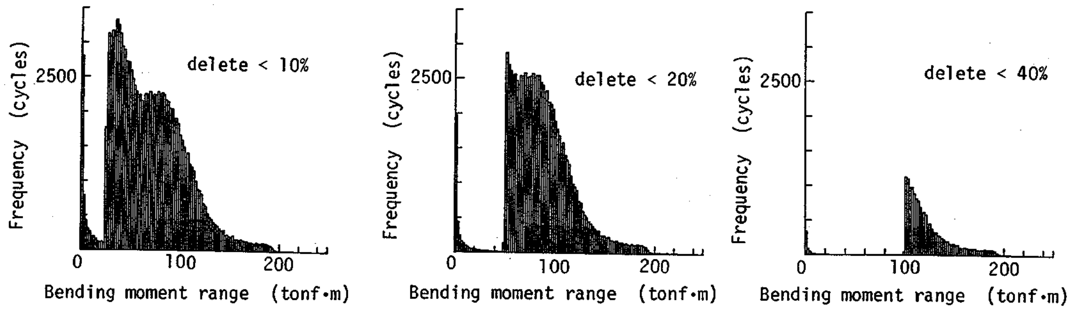

Fig. 5 (b) Frequency distribution diagrams of variable load range.

3. METHOD OF TEST

(1) Specimens

The tested steel was SM 58 of plate thickness 12.5 mm. The mechanical properties and chemical composition are given in Table 2. The configurations and dimensions of specimens are shown in Fig. 6. Fatigue damages in steel bridges occur at locations where high tensile residual stresses exist. Therefore, tensile residual stresses were introduced in the specimens performing welding in a derection perpendicular to cracking as shown in Fig. 6. The specimens were cut out from a flat plate, one side of which was bevelled and welded, followed by gouging on the other side and welding, after which the thickness was reduced for finishing. The welding conditions are shown in Table 3. The cracks, as they grow, pass the parts of heat affected zone (HAZ) and base metal (BM). The HAZ parts were used for introducing precursory cracks and measurements of crack propagation were done in the BM parts.

The residual stress distribution and the condition of redistribution accompanying crack growth are shown in Fig. 7. It can be seen that a high tensile residual stress exists at a tested section.

(2) Method of Test

The fatigue crack growth tests were performed using an electro-hydraulic servo fatigue testing machine of dynamic capacity 5 ton. The fatigue crack growth threshold stress intensity factor range under the condition of constant-amplitude stress was obtained by ΔK decreasing tests. Stress ratio is zero in all constant-amplitude loading tests. Fatigue crack lengths at this time were obtained by compliances measured by strain gages attached at the backs of the specimens, with the loads reduced approximately 5 percent when the cracks had grown a designated amount (0.15 mm in this particular study). These tests were all performed automatically by personal computer (NEC PC 9801). Crack lengths were also measured supplementary by traveling microscope (50 x). The stress intensity factor range ΔK was determined by the following equation :[26]

Table 2 Mechanical properties and chemical compositions.

Mechanical properties			Chemical compositions				
yield strength (MPa)	tensile strength (MPa)	elongation (%)	C	Si	Mn	P	S
			x100(%)			x1000(%)	
640	690	34	8	24	166	20	4

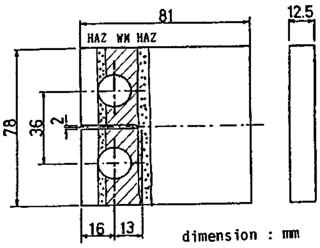

Fig. 6 Specimen with weld perpendicular to cracking.

Table 3 Welding conditions.

wire shield gas	YM-60A, ϕ1.2 Ar 90% + CO 10%
welding current	1st side : 250A 2nd side : 320A
arc voltage	1st side : 29V 2nd side : 31V
welding speed	1st side : 20cm/min 2nd side : 20cm/min

(1st side = face)

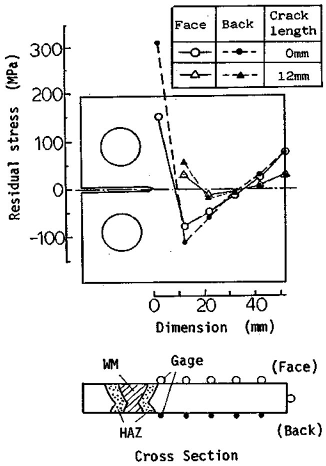

Fig. 7 Residual stress distributions of specimen.

$$\Delta K=\Delta P/B\sqrt{W}\,(2+\alpha)/(1-\alpha)^{3/2}\times(0.886+4.64\,\alpha-13.31\,\alpha^2+14.72\,\alpha^3-5.6\,\alpha^4) \quad (1)$$

where, ΔP is load range, B is plate thickness of specimen, a is crack length, W is width of specimen, and α is a/W (see Fig. 6).

4. TEST RESULTS AND CONSIDERATIONS

(1) Constant-Amplitude Load Tests

The relationship between fatigue crack grwth rate da/dN and stress intensity factor range ΔK is illustrated in Fig. 8. The two have a linear relationship on logarithmic paper at the part of $da/dN > 5\times10^{-7}$ mm/cycle, and it can be seen that the Paris law is valid. As for da/dN, it is reduced sharply from around 1×10^{-7} mm/cycle. The fatigue crack growth threshold stress factor intensity range ΔK_{th} is 2.1 MPa$\sqrt{m}$.

On application of the method of least squares to test results of fatigus crack growth rate above 10^6 mm/cycle,

$$da/dN=1.03\times10^{-8}\ (\Delta K)^{3.01}$$

is obtained.

Fig. 9 illustrates the relationship between backside strain and load. This figure shows that compliance is constant and linear up to the point of minimum load and that closure of crack has not occurred.

The equivalent stress intensity factor for variable-amplitude load fluctuation described in the subsection below is calculated by Eqs. (2) and (3).

$$da/dN=\begin{cases}C\cdot\Delta K^m & (\Delta K>\Delta K_{th})\\ O & (\Delta K\leqq\Delta K_{th})\end{cases} \quad (2)$$

$$da/dN=C\,(\Delta K^m-\Delta K_{th}^m) \quad (3)$$

In general, Eq. (3) is said to express the fatigue crack growth behavior very well around the vicinity of ΔK_{th} better. The two relationships are shown in Fig. 8, and compared with experimental values, it can be seen that Eq. (2) is on the higher side and Eq. (3) on the lower side in the vicinity of ΔK_{th}. However, the difference between the two equations is small according to the experimental results here since there is a linearity in the $da/dN-\Delta K$ relationship due to the influence of tensile residual stress. Incidentally, on obtaining the sum of the squares betweem experimental values and estimated values according to the regression equation at growth rates below 10^{-5} mm/cycle, the ratio between the two is 1.0004.

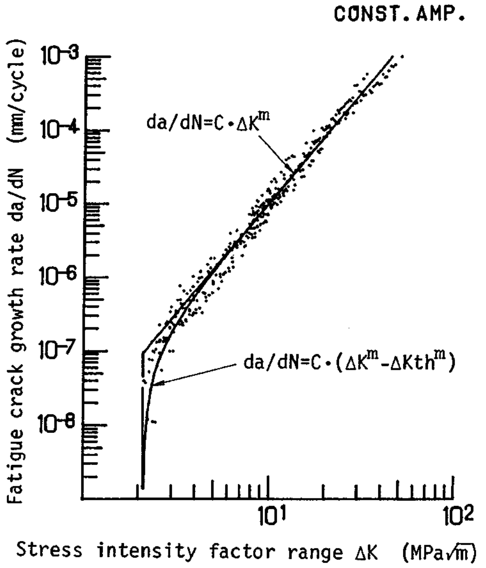

Fig. 8 Relationship between da/dN and ΔK under constant amplitude loading.

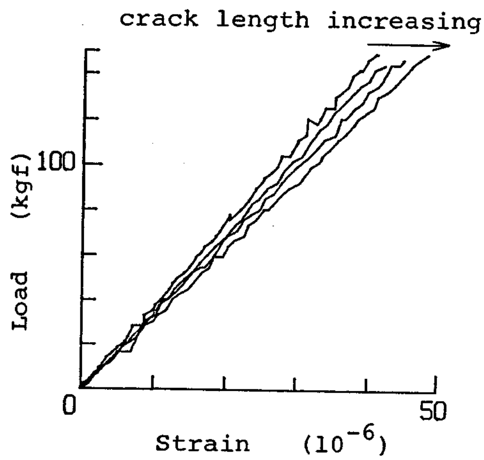

Fig. 9 Relationship between load and backside strain.

(2) Equivalent Stress Intensity Factor Range

Fatigue crack growth behavior under variable load is expressed dividing according to a certain number of cycles of stress, or block, and obtaining the average-type behavior for the block. The equivalent stress intensity factor range ΔK_{eq} deduced by the linear damage rule is used at this time.

$$\Delta K_{eq}=[(\sum \Delta K_i^m N_i/\sum N_i)]^{1/m}$$

(3) Fatigue Crack Growth under Variable-Amplitude Load Fluctuations

The relationship between average crack growth rate $\overline{da/dN}$ and the equivalent stress intensity factor range ΔK_{eq} is shown Fig. 10. The solid line in the figure is the mean line, μ, of fatigue crack growth rate under constant-amplitude load, and the broken lines are $\mu \pm 2\sigma$ (σ : standard deviation). The solid marks in the figure indicate the test results for $\Delta K_{min} > \Delta K_{th}$, that is, all stress cycles are above ΔK_{th} and the open marks the results for $\Delta K_{min} < \Delta K_{th} < \Delta K_{max}$. Hereafter, the former will be called Case I and the latter Case II (see Fig. 11), and the test results are examined divided into these two domains.

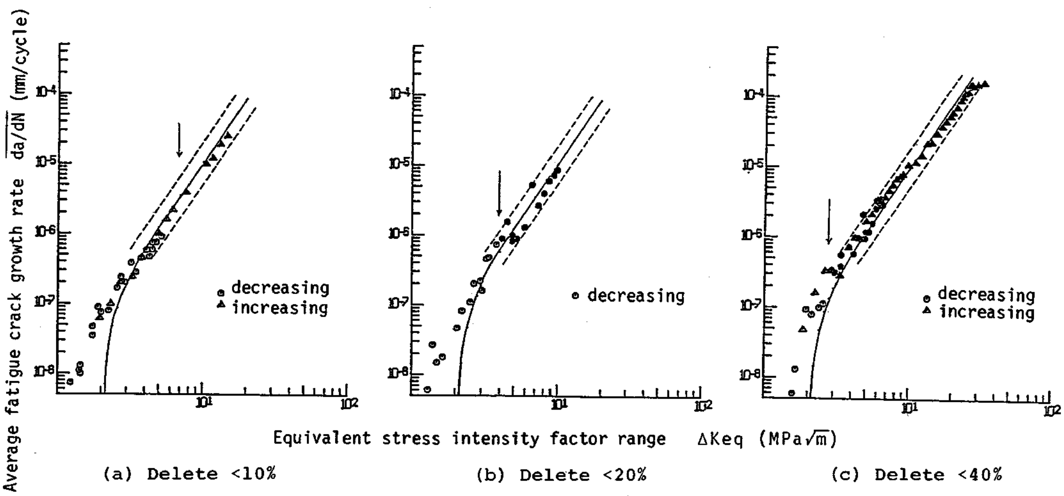

Fig. 10 Relationship between $\overline{da/dN}$ and ΔK_{eq}. ($\Delta K_{min} > \Delta K_{th}$, solid marks).

a) Case I

When all stresses are above ΔK_{th}, it has been ascertained even in past studies that the linear damage rule is valid irrespective of type of load or sequence of load such as random or block, and the same results have been obtained in these tests also. In effect, the relation between ΔK_{eq} determined by the experiments shown in the figure and $(\overline{da/dN})_{est}$ coincides with the fatigue crack growth behavior under constant-amplitude load.

b) Case II

The fatigue crack growth behavior under variable loads straddling the threshold is shown in **Fig.** 12. The abscissa shows the equivalent stress intensity factor ΔK_{eq} obtained from all ΔK.

The growth rate $(\overline{da/dN})$ gradually decreases with all variable amplitude loading tested as ΔK_{eq} declines, and a sudden reduction in $\overline{da/dN}$ is not seen as in the neighborhood of ΔK_{th} in constant-amplitude load tests. That is, even when ΔK_{eq} is below ΔK_{th}, there is apparently crack growth. If it is considered that ΔK_{th} does not vary as excessively small stresses are repeated, it may be considered that the fatigue crack growth threshold value for ΔK_{eq} is when the maximum value ΔK_{max} amongst variable loads is equal to ΔK_{th}. Consequently, the higher that the deletion level of the testing variable stress is made, the higher will be ΔK_{eq} in relation to ΔK_{max}, and the growth threshold value will be apparently high. Because of this, different fatigue crack growth curves will be produced depending on the stress spectrum.

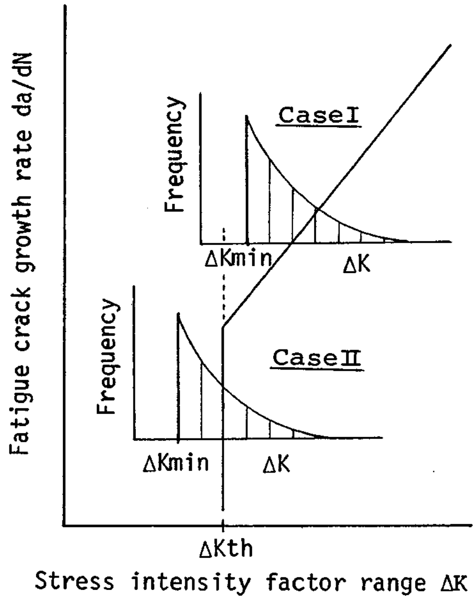

Fig. 11 Schimatic of ΔK frequency distribution Case I and Case II.

The three curves in **Fig.** 12 respectively predict fatigue crack growth amounts applying the linear damage rule according to one of the following :

① ΔK_{th} is ignored.

② The growth rate is expressed by two straight lines (Paris law and ΔK_{th}). (Eq. 2)

③ Curve including ΔK_{th} (Eq. 3)

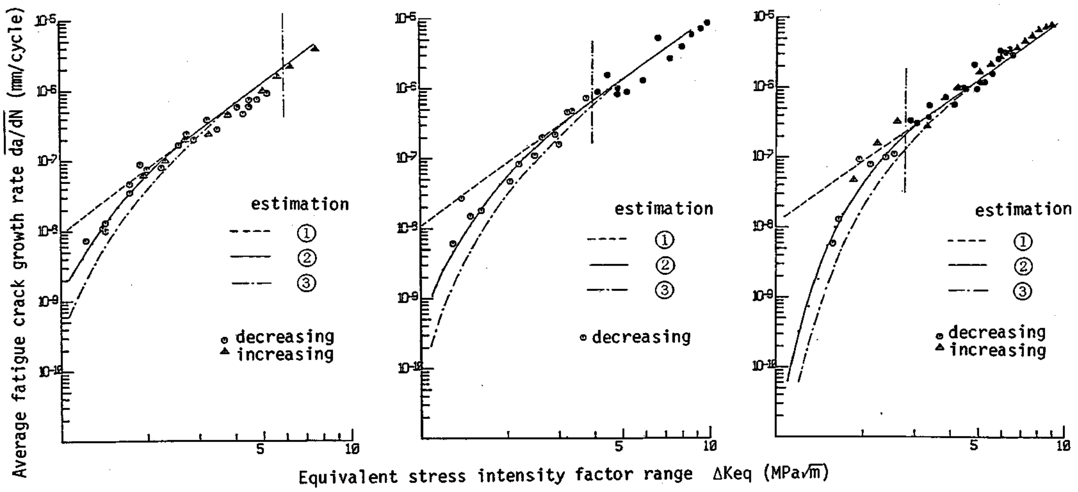

Fig. 12 Relationship between $\overline{da/dN}$ and ΔK_{eq}. ($\Delta K_{min} < \Delta K_{th}$, open marks)

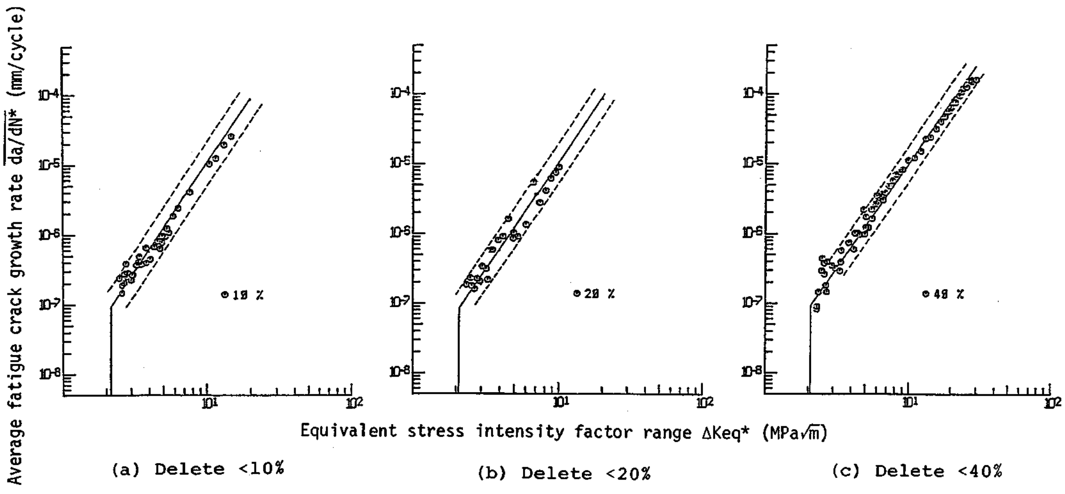

Fig. 13 Relationship between $\overline{da/dN^*}$ and ΔK_{eq}^*.

In the estimation according to ① in which the threshold is not considered, the evaluation will be on the conservative side. Regarding the estimated value according to ③, the experimental value is larger. In contrast, it may be seen that the estimated value $(\overline{da/dN})_{est}$ according to ② in which evaluation is made on somewhat the conservative side near ΔK_{th} predicts well the fatigue crack growth behavior under variable load. Because of this, it is thought that near the threshold there is an acceleration effect albeit slight due to repetitions of stress below the growth threshold value in relation to the same ΔK compared with the condition under a constant-amplitude load. This trend is seen for all stress spectra.

Fig. 13 is a rearrangement of experimental data considering that only components above ΔK_{th} amongst variable-amplitude load fluctuation components contribute to fatigue crack growth. In this figure, the abscissa gives the equivalent stress intensity factor range ΔK_{th}^* obtained for values of ΔK higher than ΔK_{th}, and the ordinate the amount of crack growth for cycle above ΔK_{th}. Experimental values arranged by such a method coincide with the fatigue crack growth relationship (solid line : average μ; broken line : average $\mu \pm 2\sigma$) under constant-amplitude stress. Hence, it is clear from this also that the influences of acceleration effects due to excessively small stresses below the threshold ΔK_{th} are so small as to be of no significance.

According to the foregoing, a slight acceleration effect due to cycles of stress lower than ΔK_{th} can be seen under variable load compared with the fatigue crack growth behavior under constant-amplitude load. It may be said that fatigue crack growth rate under such a condition can be estimated with ample accuracy by the method of ②.

5. CONCLUDING REMARKS

Variable stresses occurring in highway bridge members due to traffic loads were obtained by computer simulations, and the fatigue crack growth behaviors when subjected to such variable stresses, especially centering on the vicinity of the fatigue crack growth threshold ΔK_{th}, were studied. In this study, assuming welded joints, specimens pieces such that tips of fatigue cracks in specimens would always be tensile residual stress fields were used.

The principal results obtained in this study were the following :

(1) In case stress ranges of variable stresses are all higher than ΔK_{th}, the relationship between the equivalent stress intensity factor range ΔK_{eq} determined by the linear damage rule and the fatigue crack growth rate da/dN on average coincides with the da/dN-to ΔK relationship under constant-amplitude load.

(2) In case many stress ranges in which variable stresses will be less than ΔK_{th} are contained, there is slight acceleration effect due to cycles of stress below ΔK_{th} seen, but this is of a degree that can be ignored.

(3) When the linear damage rule is applied using the Paris law and ΔK_{th} obtained in fatigue crack growth tests in a constant stress range, it is possible to estimate fatigue crack growth under variable amplitude load fluctuations, including the influences of cycles of stress below ΔK_{th}, with adequate accuracy.

ACKNOWLEDGEMENTS

The authors sincerely thank Messrs. Akihiko Ohta and Saburo Matsuoka of the National Research Institute for Metals, the Science and Technology Agency, for much valuable advice in carrying out this study.

REFERENCES

1) Takamura, A. : Techniques for Maintenance (1) Roads, Jour. of JSCE, Vol. 68, No. 10, pp. 39 ~42, 1983.
2) Nishikawa, K. : Fatigue and Repair in Highway Bridges, Bridge and Foundation Engineering, Vol. 17, No. 8, pp. 19~23, 1983.
3) Tezuka, S. and Ikeda, Y. : Repair of Plate Girder End Notch, Bridge and Foundation Engineering, Vol. 17, No. 8, pp. 56~59, 1983.
4) Imai, H., Yamasaki, T., Fujino, K. and Mizumoto, Y. : Damages and Repairs in Steel Structures, Bridge and Foundation Engeneering, Vol. 17, No. 8, pp. 65~72, 1983.
5) JAR : Specifications for Highway Bridge, 1980.
6) Barsom, J. M. : Fatigue Crack Growth under Variable Amplitude Loading in ASTM A514-B Steel, ASTM STP536, 1973.
7) Kitagawa, H. and Fukuda, S. : Fatigue Crack Propagation in Steel Plate under Random Loading, Proc. of JSME(1), Vol. 43, No. 371, 1977.
8) Haku, I. and Okamura, H. : Fatigue Crack Propagation under Random Stable Loading, Proc. of JSME(1), Vol. 43, No. 371, 1977.
9) Haku, I. and Okamura, H. : Fatigue Crack Propagation under Random Stable Loading, Proc. of JSME, Vol. 48, No. 435, 1982.
10) Naitoh, Y. and Okamura, H. : Fatigue Crack Propagation under Variable Loading, Proc. of JSME, Vol. 44, No. 386, 1978.
11) Yamada, K. : Fatigue Crack Growth Rate of Structual Steels under Constant and Variable Amplitude Block Loading, Proc. of JSCE Struct. Eng., Vol. 2, No. 2, 1985.
12) Kikukawa, M., Johno, M. and Kondoh, Y. : Fatigue Crack Propagation under 2-step Loading near Kth, Jour. of JSMS, Vol. 27, No. 302, 1978.
13) Kikukawa, M., Johno, M., Kondoh, Y. and Mikami, S. : Crack Openning-closure Behavior and Measurement of Crack Growth Rate under Variable Amplitude Loading, Proc. of JSME, Vol. 48, No. 486, 1982.
14) Johno, M., Kanaya, T., Sugata, A. and Kikukawa, M. : Retardation Behavior of Fatigue Crack Propagation by Single Over Loading under Plane Strain Condition, Jour. of JSMS, Vol. 32, No. 363, 1983.
15) Kikukawa, M., Johno, M. and Kondoh, Y. : Fatigue Crack Propagation and Openning-closure Behavior in Low K Region under 2- and 3-step Loading, Jour. of JSMS, Vol. 28, No. 313, 1979.
16) Kikukawa, M., Johno, M. and Kondoh, Y. : Evaluation of Fatigue Crack Growth Rate in Low K Region under Variable Loading, Proc. of JSME(A), Vol. 47, No. 417, 1981.
17) Kobayashi, H., Ogawa, T., Saitoh, N., Nakamura, H. and Nakazawa, H. : Fatigue Crack Propagation and Crack Openning-closure under Program Loading, Proc. of JSME, Vol. 50, No. 458, 1984.
18) Kobayashi, H. et al : Fatigue Crack Propagation under P-distribution Program Loading, Proc. of JSME (A), Vol. 50, No. 452, 1984.
19) Iwasaki, T., Katoh, A. and Kawahara, M. : Effect of Load Frequency Distribution on Fatigue Crack Growth under Random Loading, Proc. of JSS, No. 156, 1984.
20) Sakakibara, A. and Horikawa, K. : Fatigue Crack Propagation under Repeated Variable Amplitude Loading in Welding Tensile Residual Stress Fields (in Low K Region), Jour. of JWS, Vol. 4, No. 4, pp. 715~722, 1986.
21) Fisher, J. W. and Mertz, D. R. : Steel Bridge Members under Variable Amplitude Long Life Fatigue Loading, National Coopera tive Highway Reserch Program Report 267, 1983.
22) Miki, C., Gotoh, Y., Yoshida, H. and Mori, T. : Computer Simulation Studies on the Fatigue Load and Fatigue Design of Highway Bridges, Proc. of JSCE Struct. Eng., Vol. 2, No. 1., pp. 37~46, 1985.
23) Albrecht, P. and Yamada, K. : Simulation of Service Fatigue Loads Short-span Highway Bridges, ASTM STP671, 1979.
24) Fisher, J. W. et al. : High Cycle Fatigue Behavior of Steel Bridge Details, Fritz Engineering Laboratory Report, No. 386-13,

1982.
25) Sinohara, Y. et al. : Studies on Evaluation of Durability of Existing Bridges, PWRI Report, No. 2420, 1986.
26) ASTM E647-78T : Tentative Test Method for Constant Load Amplitude Fatigue Crack Growth Rates above 10^{-8} m/cycle.

(Received April 22 1987)