Structural Eng. / Earthquake Eng. Vol. 6. No. 1, 23s-30s. April 1989
Japan Society of Civil Engineers (Proc. of JSCE No. 404/I-11)

FATIGUE TESTS OF WELDED DETAILS IN LONG LIFE REGION AND FRACTURE MECHANICS ANALYSIS

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Fatigue strength of welded details in long life region, for example over five million cycles, is essential for fatigue design of bridge components, because the stress ranges measured in service are often in this range. Constant amplitude fatigue tests on 200 mm long gussets welded to tensile plates and tensile flange of beams and on 200 mm long cover plates subjected to low stress ranges were carried out, and constant amplitude fatigue limits were evaluated. The test results on 200 mm long gussets were compared with fatigue crack propagation life computed using the Monte Carlo simulation technique. The analytical results were generally in good agreement with the test results in the finite life region. However, the predicted fatigue limit using a threshold value of stress intensity factor range was lower than the runout level of test data.
Keywords : fatigue, welded joint, fracture mechanics, Monte Carlo simulation

1. INTRODUCTION

Fatigue design is not required for the structural components of steel highway bridges by the Standard Specification for Highway Bridges except for orthotropic steel decks[1]. In the recent years, numerous fatigue damages due to extremely heavy traffic have been reported and extensive study on fatigue for highway bridges has become urgent. From the stress measurements on bridges in service, it has been recognized that the service stresses distribute in the low stress range[2], so the fatigue evaluation of welded details subjected to low stress range, i. e. in long fatigue life region, is found to be very important. However, only a few fatigue tests for welded details were carried out in the long fatigue life region, for example more than five million cycles, because of enormous time and cost involved.

In this study, constant amplitude fatigue tests were carried out on two tensile specimens with welded gussets and two bending beams with gussets and cover plate. The applied stress ranges were selected in such a way that the test data would fall in the long life region. Fracture mechanics analysis was also carried out for the gussetted detail to obtain the analytical fatigue crack propagation life in the long life region. The Monte Carlo simulation technique was used to select the initial conditions for the analysis. Then the fatigue limit under constant amplitude load in the design $S-N$ diagram was studied by using the test results and the analytical results.

2. FATIGUE TESTS OF WELDED DETAILS IN LONG LIFE REGION

(1) Test specimens

As shown in **Fig. 1**, two tensile specimens with gussets (G 2 L series) and two bending beams with

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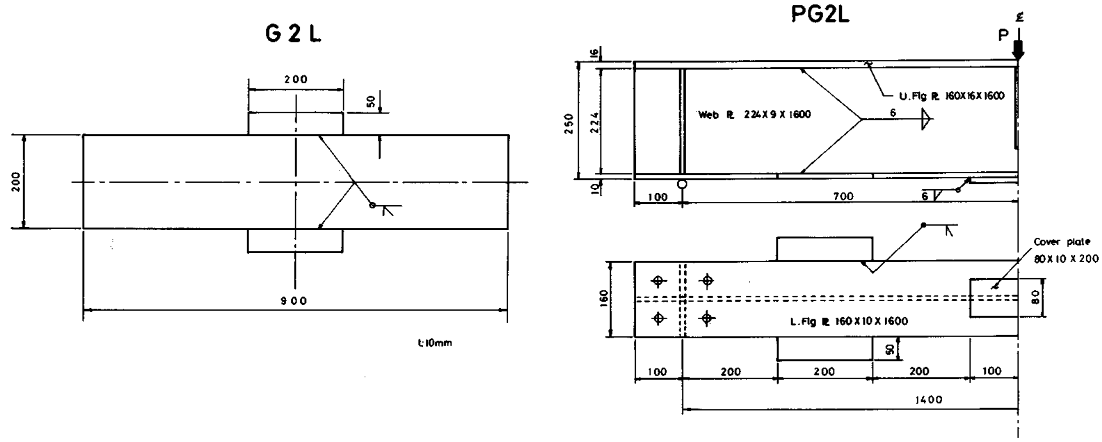
gussets and cover plate (PG 2 L series) were tested. They were made of JIS SM 50 A steel. The chemical compostion and mechanical properties of the steel are shown in Table 1. These specimens were fabricated at the same time as the previous test series[3),6)]. The data can, therefore, be directly comparable with the present test results. The G 2 L specimens were made by welding two gussets of 10×50×200 mm symmetrically in the plane of a base plate of 10×200×900 mm. The PG 2 L specimens had the span of 1.4 m, the beam height of 250 mm, and the tensile flange of 10×160×1 400 mm. Four gussets were welded to the tensile flange in the same manner as the G 2 L specimens. A cover plate of 10×80×200 mm was also welded to the center of the tensile flange. The gussets were butt-welded with 45 degree groove and the cover plate was fillet-welded with leg length of 6 mm. All tests were carried out in as-welded condition.



(a) Gusset Welded to Tensile Specimen (b) Gusset and Cover Plate Welded to Beam

Fig. 1 Test Specimens.

(2) Test method

The fatigue tests were carried out with Amsler type testing machine of 980 kN loading capacity. Tensile load was applied to the G 2 L specimens and three points bending load to the PG 2 L specimens. The cycling speed was about 4 Hz. Copper wires of 0.04 mm diameter were attached to the specimens. They were connected to testing machine, and stop the testing machine automatically when fatigue cracks reach to the wires.

An initial crack size and N_c were defined when the copper wire glued on the weld toe was cut. A final crack and fatigue life N_f were defined when the copper wire glued at 10 mm away from the weld toe was cut. A hole of 10 mm diameter was drilled at the crack tip emanating from the gusset end. Then another copper wire was attached about 1 mm away from the edge of the stophole in order to define the crack initiation life from the stophole. For the cover plate, cracks initiated at the weld root, therefore, N_f was defined when the crack reached the flange plate through the fillet weld. Beach mark tests were carried out to mark crack shapes on the fracture surface. The number of cycles needed for beach mark tests was excluded from N_c and N_f. Three inks of different color were also applied to the crack tip as the crack propagated. They left dye marking on the fracture surface. The fatigue tests were discontinued when a crack occurred from the stophole.

(3) Fatigue crack initiation and propagation

The fatigue test results are summarized in Tables 2 and 3. No fatigue crack was observed in the specimen PG 2 L 1 over 20 million cycles. Then the applied load range was increased by 50 percent, and the test was continued. The cracks in the cover plate in the specimen PG 2 L 2 did not propagate up to 28.8 million cycles, and the applied load was also increased by 50 percent for the retest.

Table 1 Chemical Composition and Mechanical Properties.

SPECIMEN (STEEL SM50A)		Yield Strength (MPa)	Tensile Strength (MPa)	Elongation (%)	Chemical Composition (%) C *100	Si *100	M *100	P *1000	S *1000
PG2L	L-Plate	382	519	28	16	27	129	20	10
	Web	382	529	27	16	26	132	19	6
	U-plate	382	519	29	14	30	140	20	4
G2L		402	559	26	18	28	131	15	3

Table 2 Fatigue Test Result of 200 mm Long Gusset.

Specimen No.	Toe No.	Stress Range (MPa)	Nc (×10³ cycles)	Crack Size at Nc(mm)	Nf (×10³ cycles)	Crack Size at Nf(mm)
G2L1	2	49.0	3,094	0.5	4,002	12.0
G2L2	2	49.0	1,071	1.0		
	4	49.0	1,071	1.5	2,817	11.5
PG2L1		39.2	> 20,503			
PG2L1(R)	5	58.8	634	2.4	1,285	9.4
	3	58.8	1,285	1.6	2,711	19.8
PG2L2		39.2	> 28,822			
PG2L2(R)	3	58.8	1,048	1.4		
	4	58.8	1,266	—		

(R):Retested　　1MPa=9.8kg/mm²
> :run out

Table 3 Fatigue Test Result of 200 mm Long Cover Plate.

Specimen No.	Toe No.	Stress Range (MPa)	Nc (×10³ cycles)	Crack Size at Nc(mm)	Nf (×10³ cycles)	Crack Size at Nf(mm)
PG2L1		59.0	> 20,503			
PG2L1(R)	10	88.2	1,771	—	2,204	95.0
PG2L2	10	58.6	14,155	—	27,633	75.6
	9	58.6	16,765	4.0		

(R):Retested　　1MPa=9.8kg/mm²
> :run out

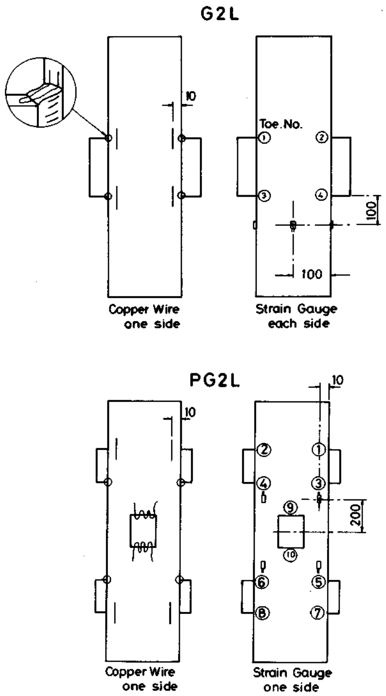


Fig. 2 Location of Copper Wire and Strain Gage.

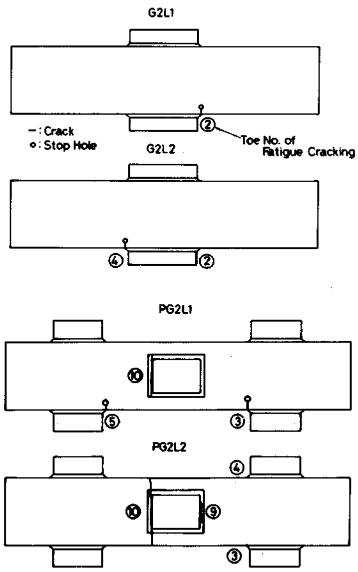


Fig. 3 Location of Fatigue Cracking.

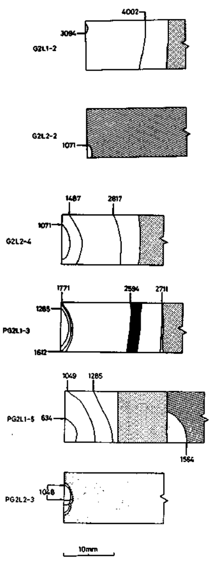


Fig. 4 Sketch of Fatigue Fracture Surface at End of Gusset.

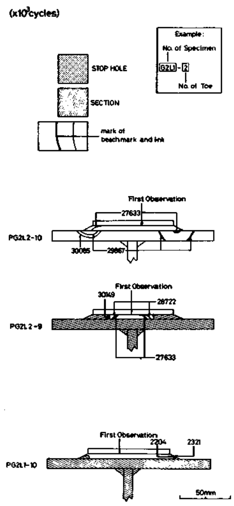


Fig. 5 Sketch of Fatigue Crack Surface at Cover Plate.

a) Fracture surfaces

During the fatigue tests, beach marking test and dye marking test were carried out. For the dye marking tests, black, red and yellow inks were applied separately into the cracks in this order and three color marks were observed on the fracture surfaces. Fig. 3 shows the initiation points of cracks in each specimen, and Figs. 4 and 5 show the schematic view of fracture surfaces based on the beach-marks and the dye-marks in each specimen. The crack shapes obtained by using dye marking method were in good agreement with those from beach-marks. But the cutting oil used for drilling stopholes and for the band saw to expose fracture surface washed partly away the dye-marks.

From the observation of the fracture surface of gussets it was found that the initial crack lenght was 0.5–2.4 mm when the first copper wire was cut. Compared with the previous test results[3], where the measured initial crack length was between 1.6–6.5 mm by using a copper wire of 0.1 mm diameter. The finer the copper wire was, the more sensitive it was to the crack. The observed crack shapes were an elliptical crack represented by G 2 L 2-4 and a semi-elliptical crack represented by PG 2 L 1-5. The aspect ratios of the cracks were about 1/2.

The fatigue cracks initiated at the root of the fillet weld at the end of the cover plate. The fillet welds of the cover plates were 6 mm in size. The throat area was too small for this detail, and it caused the cracking from the root. After the cracks reached the surface of the fillet weld, they propagated in two directions into the flange through the fillet weld. The fracture surface in the fillet weld were partly rusted and it was difficult to observe the shape of the initial crack and the beach-marks at the weld root.

(4) Fatigue crack initiation life and fatigue life

a) Fatigue test results

The fatigue test results of the gussets are shown in Fig. 6. For two bending specimens, a stress range of σ_r=39 MPa was first applied and no cracks occurred over more than 20 million cycles. Then the applied load was increased by 50 percent, and the test was continued. As a result, four cracks initiated, but two of them did not propagate. Using the previous test results of the same gussets and the present test data, S-N diagrams corresponding to mean $\pm 2s$ (s : standard deviation) were calculated by using the least square method, as shown by the straight lines in Fig. 8.

The test results of the cover plate are shown in Fig. 7. The cracks were found in both sides of a cover plate, when testing at σ_r=58.6 MPa and one of the cracks did not reach to the final size before the beam failed. No crack was observed in the other cover plate up to 20.5 million cycles. When the retest was carried out for this beam, a crack initiated in the cover plate. For the cover plates, the fatigue cracks initiated at the weld root, and they were not visible until the cracks reached the surface. Therefore, it seems that the crack initiated at the cycles less than the observed N_c at the weld root.

b) Fatigue life

Fig. 8 shows the σ_r-N_f diagram of gussets. In order to compare them with allowable stress range specified in the design standard, the lower bound of the S-N diagram (i.e. mean$-2s$) is obtained. The

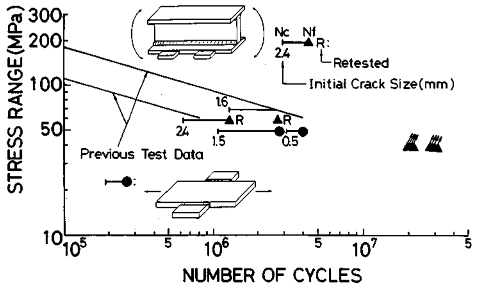


Fig. 6 Present Fatigue Test Result of 200 mm Long Gusset in Long Life Region.

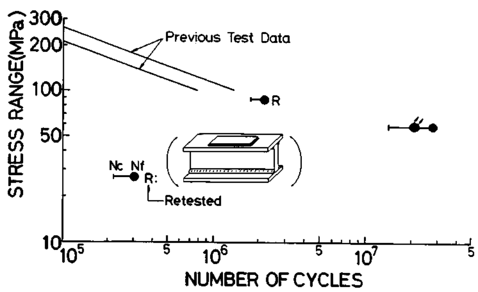


Fig. 7 Present Fatigue Test Result of 200 mm Long Cover Plate in Long Life Region.

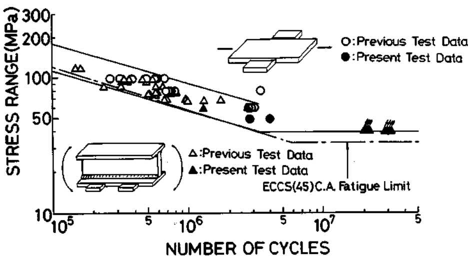


Fig. 8 Summary of Fatigue Test Result of 200 mm Long Gusset.

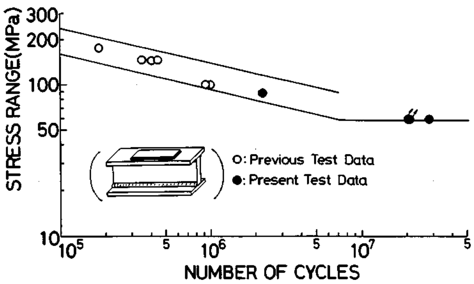


Fig. 9 Summary of Fatigue Test Result of 200 mm Long Cover Plate.

constant amplitude fatigue limit was defined as σ_r=40 MPa, because at σ_r=39.2 MPa no cracks occurred in the present tests. The number of cycles corresponding to the fatigue limit is about 4 million cycles. The ECCS Fatigue Design Recommendation of Steel Structures uses design S-N diagram corresponding to the lower bound (mean$-2s$) of test data. It specifies the fatigue strength of this type of gussent at 2 million cycles as 45 MPa and the fatigue limit is σ_r=33 MPa at 5 million cycles[5]. The lower bound of test data is in good agreement with that the ECCS design S-N diagram in higher stress range region, while the observed constant amplitude fatigue limit is 20 percent higher than the specified value of ECCS[5].

Fig. 9 shows the σ_r-N_f diagram of the cover plates. The previous test data[6] of the same cover plate are also plotted and the least square method is used to obtain the upper and the lower bound S-N diagrams. The fatigue limit is defined as σ_r=59.0 MPa, at which no crack was observed. The corresponding number of cycles is about 7 million. It seems that the value of the fatigue limit may be less than the present data, because one cover plate end showed fatigue cracking at 27 milion cycles.

3. FATIGUE LIFE ESTIMATION USING MONTE CARLO SIMULATION TECHNIQUE

Since fatigue test in long life region is both costly and time-consuming, it may not be feasible to obtain a series of experimental data. The fracture mechanics analysis of fatigue crack propagation life is the alternative way to predict the fatigue life in the long life region. Hence, the present test results were compared with the fatigue crack propagation life estimated by the fracture mechanics analysis. The authors have shown that the fatigue crack propagation life and the scatter of the test data can be estimated by considering the scatter of the initial crack sizes, the weld shapes and so on[7]. The initial conditions in the analysis were given by using the Monte Carlo simulation technique. The same simulation technique was used to compute fatigue crack propagation of the gusset specimens.

(1) Analytical procedure

Fatigue life N_f can be defined as the sum of the crack initiation life N_c and the crack propagation life N_p. In the case of welded joints subjected to relatively high stress ranges, fatigue crack initiates at the early stage of fatigue life. In the long life region with low stress ranges, N_c seems to increase. The assumption of $N_f \fallingdotseq N_p$ may underestimates the fatigue life. It gives, however, safer side estimation in fatigue design. Thus, the assumption of $N_f = N_p$ is proved to be justified. The N_p represents the number of cycles necessary for the crack to propagate from the initial size a_0 to the final size a_f, and can be computed by using the following equation[3].

$$N_p=\int_{a_0}^{a_f} \frac{1}{c(\Delta K^m-\Delta K_{th}^m)} da \cdots\cdots (1)$$

where c, m : material constants,

ΔK : range of stress intensity factor,

ΔK_{th} : threshold value of stress intensity factor range.

ΔK is the range of K, which represent the stress state of a crack tip and ΔK_{th} indicates the value of ΔK, below which the crack does not propagate. ΔK can be expressed as follows :

$$\Delta K=\sigma_r\sqrt{\pi a}\cdot F \quad (2)$$

where σ_r : stress range,

a : length of crack,

F : correction factor.

The correction factor F can be determined by the following equation which separates the effect of each parameter.

$$F=F_sF_eF_tF_g \quad (3)$$

where F_s : free surface correction factor,

F_e : crack shape correction factor,

F_t : finite plate width correction factor,

F_g : geometry correction factor.

Table 4 Correction Factor for Crack Emanating from Gusset End.

	Fs	Fe	Ft	Fg
Edge Crack	1.12	1.0	1.0	$F_{g1} \times F_{g2}$
Semi-elliptical crack	1.12-0.12a/b	I/E_k	1.0	$F_{g1} \times F_{g2}$
Corner Crack	1.38	I/E_k	1.0	$F_{g1} \times F_{g2}$

The test results showed that the fatigue crack initiated at the weld toe of the gusset end and propagated in the direction perpendicular to the principal axis, as shown in Fig. 10. In the fracture surface, three types of crack propagation modes were observed, as shown in Fig. 11. They were : an edge crack which initiated at the weld toe (type 1) ; an elliptical crack which initiated at the center of the plate (type 2) ; and a quarter elliptical corner crack which initiated at the corner of plate (type 3). In this analysis, these three types of crack were assumed to have equal chances to occur. The correction factors for each type are shown in Table 4. The aspect ratio of the crack, a/b, for the elliptical crack and the quarter elliptical corner crack was assumed as 1/2, and therefore E_k was 1.211. The correction factor F_{g1} accounts for the effect of the stess concentration caused by the local geometry of the weld toe, and F_{g2} accounts for the global effect due to the gusset. The correction factor F for type 2 and type 3 cracks were computed by considering that the type 2 and type 3 cracks became type 1 crack after the crack propagate through the plate thickness. To obtain the distribution of the weld toe profiles, measurements were carried out and the results were used in the simulation. The simulation was carried out by using $C=9.69\times10^{-9}$, $m=2.9$, $\Delta K_{th}=2.5\,\mathrm{MPa}\sqrt{m}$, which were obtained in the National Research Institute for Metals (NRIM) for SM 50B steel welded joints[8]. The simulation was repeated 1 000 times at each stress range level.

(2) Analytical result

Fig. 12 shows the computed crack propagation life by the histogram and the upper and the lower bound S-N diagrams. In the case of fatigue life in large stress range levels, the upper and the lower bound values can be shown by computing mean $\pm 2\,s$ (s : standard deviation). However, in the case of fatigue life in the

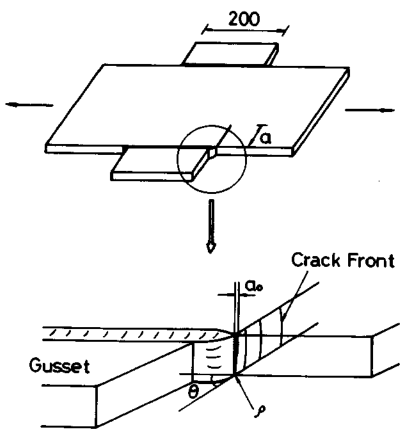


Fig. 10 Analytical Model of Crack Emanating from Gusset End.

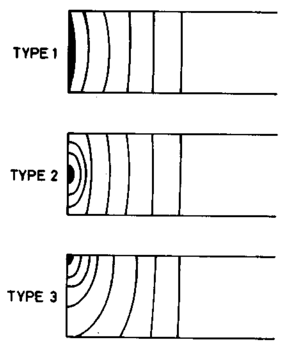


Fig. 11 Three Modes of Fatigue Crack Shape.

small stress range levels, the N_p distribution distorted towards the left [7]. Therefore, the lower bound value was assumed to be the 25th value (2.5 percent failure) from the lowest value of 1 000 simulations and the upper bound value from the highest value. It is found that the lower bound value of the simulation result is in good agreement with the ECCS design S-N diagram up to about 5 million cycles. In the long fatigue life region, i. e. more than 5 million cycles, the fatigue limit computed by using $\Delta K_{th}=2.5$ MPa$\sqrt{m}$ is smaller than the fatigue limit estimated from the previous test results and that specified by ECCS. The difference seems to come from the assumption that one third of the cracks are edge cracks, and that the product of F_{g1} and F_{g2} represent the effect of stress concentration. Both assumptions gave rather severe initial conditions, and yielded low fatigue limit estimation. It should be noted, however, that more test data is needed to determine constant amplitude fatigue limit because the analytical results showed the possibility of the lower fatigue limit.

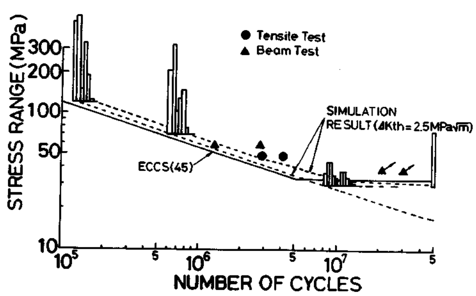


Fig. 12 Analytical Result of Crack Propagation Life Using Monte Carlo Simulation.

4. SUMMARY

A few fatigue test data of welded joints under small stress range (i. e. long life region) is available to date and it makes the fatigue assessment in this range very difficult. In this study, fatigue tests of gussets and cover plates under constant amplitude loading were carried out in the long life region. The fatigue crack propagation analysis was also carried out for the gussets. The Monte Carlo simulation technique was employed to define the initial condition of the analysis in order to evaluate the scatter of the data. The followings summarize the findings :

(1) Accordind to the tests, the constant amplitude fatigue limit of 200 mm long gusset was about 40 MPa and it was about 20 percent higher than that specified by the ECCS Fatigue Design Recommendition. The 200 mm long cover plate showed fatigue limit of about 59 MPa. Because the crack at the weld root of cover plate can hardly be seen, the fatigue limit may be smaller than this value. Actual cover plates have smaller constant amplitude fatigue limits, because the longer the cover plate is, the smaller the fatigue limit results.

(2) When the copper wire of 0.04 mm diameter was glued at the toe of the gusset, it detected the crack of about 0.5–2.4 mm long. The shape of cracks were also monitored on the fracture surface by dye marking technique using three colors of ink and by beach marking technique.

(3) The fracture mechanics analysis using the Monte Carlo technique proved to have estimated reasonable fatigue crack propagation life compared with the test results. The computed constant amplitude fatigue limit was, however, smaller than the test data.

ACKNOWLEDGEMENT

This study was partly supported by the Grant-in Aid for Scientific Research (C) from the Japanese Ministry of Education, Science and Culture. Much help was received from Mr. T. Shinoda for preparing the manuscript. They are highly appreciated.

REFERENCES

1) Japan Road Association : Standard Specification for Highway Bridges, 1980. 2 (in Japanese).

2) Public Works Research Institue, Ministry of Construction : Evaluation of Durability of Existing Bridges—Investigation for more advanced technology, Public Works Research Institue Report No. 2420, 1987.

3) Yamada, et al. : Fatigue of Tensile Plate with Gussets and Stopholes as Crack Arrest, Proc. of JSCE, No. 341, pp. 129–136, 1984. 1 (in Japanese).

4) Yamada, K. and Hirt, M. A. : Parametric Analysis of Fatigue Life Using Fracture Mechanics, Proc. of JSCE, pp. 55-64, 1982 (in Japanese).
5) ECCS, TC-6 : Recommendations for the Fatigue Design of Steel Structures, 1985.
6) Moroto, K. and Yamada, K. : Fatigue Strength and Allowable Fatigue Stress Range of Cover Plate, Journal of JSCE, Vol. 33 A, pp. 403-410, 1987 (in Japanese).
7) Nagatsu, S., Yamada, K. and Mitsugi, Y. : Evaluation of Scatter of Fatigue Life of Welded Details Using Fracture Mechanics, Journal of JSCE, Vol. 34 A, pp. 451-458, 1988 (in Japanese).
8) NRIM Fatigue Data Sheet, Technical Document No. 3 : Fatigue Crack Propagation Properties in Arc-Welded Butt-Joints of High Strength Steels for Welded Structures, National Research Institute for Metals, 1984 (in Japanese).
9) Yamada, K. et al. : Fatigue Strength of Tensile Members with Welded Gussets and Life Estimation by Fracture Mechanics, IIW Doc. XIII-1204-86.

(Received April 11 1988)