Structural Eng. / Earthquake Eng. Vol. 7. No. 2, 283s-291s. October 1990
Japan Society of Civil Engineers (Proc. of JSCE No. 422/I-14)

FATIGUE OF LARGE-SCALE WELDED GIRDERS UNDER SIMULATED HIGHWAY LOADINGS

By Chitoshi MIKI, Yukihiro TOYODA**, Takeshi MORI*** and Naohiro ENOKIDO*****

In order to examine the fatigue strengths of welded bridge details subjected to traffic loading, four large-scale welded girders were tested with various gusset details, transverse stiffener and cover-plates. The results were compared with the fatigue strengths of joint specimens and the allowable stresses in some specifications. Furthermore, the applicability of drilling holes as a retrofitting technique was investigated.
Keywords : fatigue, highway bridge, simulated loading, structural welded detail

1. INTRODUCTION

Many cases of fatigue damage in highway steel bridges have been reported in recent years[1]. It is thought that damage to highway bridges due to fatigue will become greater than ever, when the increases in vehicle weights and traffic volumes of recent are taken into consideration. Consequently, it is necessary to establish a fatigue design method, together with adopting structural details of high fatigue resistance.

In case of attempting to experimentally investigate the fatigue strengths of welded structures, fatigue tests under constant stress amplitude are usually performed on small joint specimens which model the structural welded details. However, it may be expected that the fatigue strength of a welded joint obtained in this way and that of a welded joint in an actual bridge may be different due to the so-called size effects. The size effects include the states of stress concentrations, the condition of occurrence of weld defects, and levels of weld residual stresses. Furthermore, actual joints are subject to very complicated variable loads because vehicles of various kinds and weights pass over actual bridges. These variable loads may result in the different fatigue behavior.

When such circumstances are considered, it becomes necessary for the fatigue strengths of various welded details of a bridge to be investigated performing fatigue tests under variable load conditions as near as possible to actual loads by using specimens with member sizes and welding methods as close as

* Member of JSCE, Dr. Eng., Professor, Dept. of Civil Eng., Tokyo Institute of Technology (2-12-1, O-okayama, Meguro-ku, Tokyo 152)
** Member of JSCE, M. Eng., Central Research Institute of Electric Power Industry (formerly Graduate Student, Tokyo Institute of Technology)
*** Member of JSCE, Dr. Eng., Assistant Professor, Dept. of Civil Eng., Hosei University (formerly Tokyo Institute of Technology)
**** Kawasaki Heavy Industry (formerly Student, Tokyo Institute of Technology)

practicable to the actual bridges.

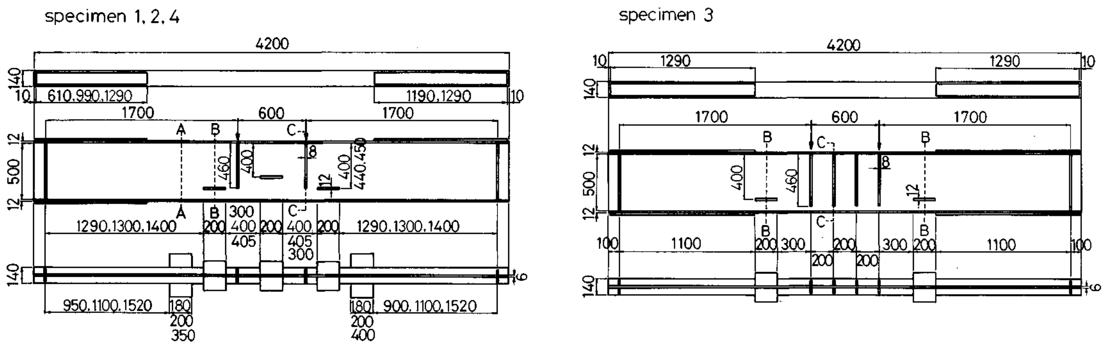
There have been very few studies up to now of variable load tests performed using large-scale welded structural members. In this study large-scale welded plate girders were used to carry out fatigue tests under variable amplitude loads such as actual highway bridges are subjected. The variable waveforms used in the tests were prepared from computer simulation[2]. Furthermore, the effects of stop holes at the tip of fatigue cracks were examined as a simple method of repairing for fatigue crack[14),15)].

2. EXPERIMENTATION METHOD

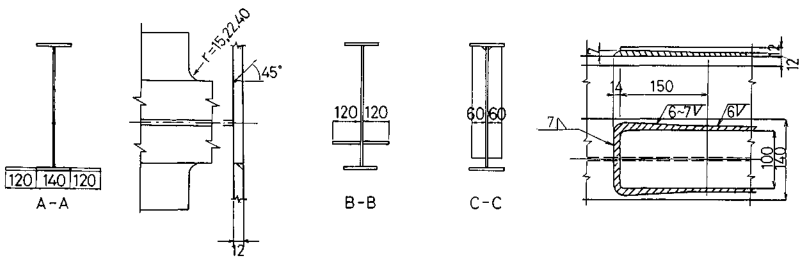
(1) Specimens

The configurations and dimensions of the welded plate girders (here-in-after referred to as "girder specimens") and details of welded joints in the girder specimens are shown in **Fig. 1** (a), (b). Four girder specimens were made with the individual specimens having flange gussets, web gussets, vertical stiffeners, and cover plates welded varying details and some of the attachment locations. The various welded joints in the girders were made in a manner that fatigue cracking would occur at approximately the same number of cycles on referring fatigue design curves for railway bridges[5)].

As shown in **Fig. 1** (b), there was a fillet at the end of flange gussets. The radii of fillets were made 15, 22 and 40 mm for specimens 1, 2 and 4, respectively. The toe of butt welds of flange and gusset was



(a) Girder Specimen

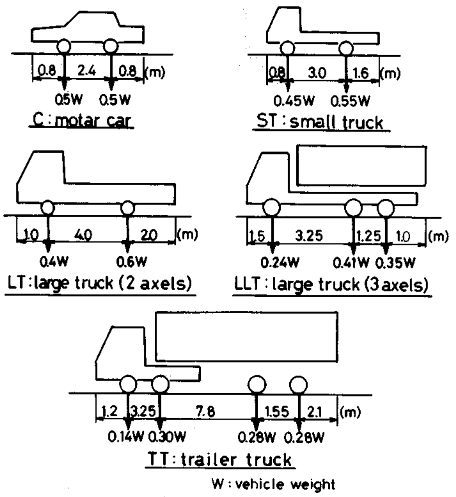


(b) Welded Details

Fig. 1 Configuration and Dimensions of Girder Specimens.

Table 1 Mechanical Properties and Chemical Composition of Steels used.

steel	thickness (mm)	yield point (MPa)	tensile strength (MPa)	elorga-tion (%)	C	Si (%) x 100	Mn	P	S (%) x 1000	remarks
SM50A	12	410	570	27	16	38	141	23	4	flange, cover plate
SM50YA	6	390	540	25	16	34	131	15	10	web
SS41	12	330	440	31	9	19	91	24	6	gusset
SS41	8	290	450	30	16	14	66	12	18	stiffener



Vehicle	Constitution	Vehicle Weight (tf)				
		mean	maximum	minimum	standard deviation	distribution
C	10%	1.2	4.0	0.5	0.77	normal
S T	5%	3.1	8.0	0.8	1.79	normal
L T	25%	8.1	30.0	1.0	3.2	normal
L L T	50%	17.7	45.0	2.0	6.1	normal
T T	10%	22.2	66.0	6.0	9.6	log-normal

Fig. 2 Model of Vehicles.

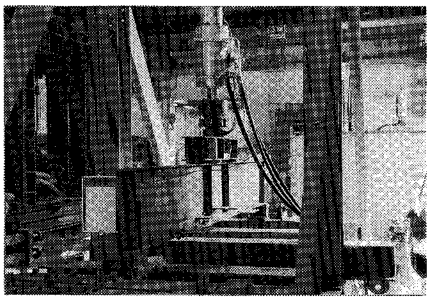


Photo 1 A View of Fatigue Testing.

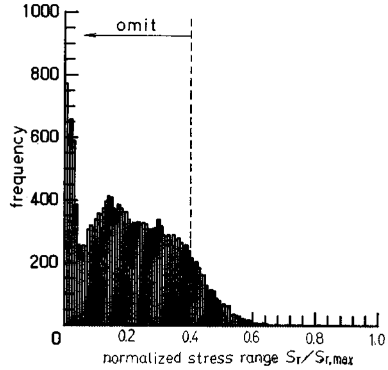


Fig. 3 Histogram of Stress Range.

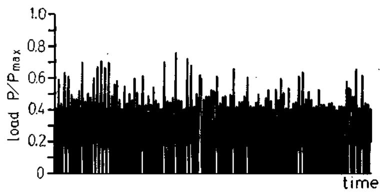
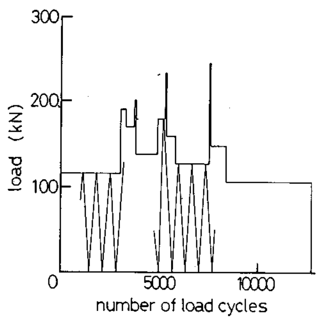


Fig. 4 A Part of Waveform.



Block number	load range (kN)	cycles
1	116	3050
2	191	260
3	170	416
4	202	65
5	138	1085
6	180	429
7	234	18
8	223	25
9	159	464
10	127	1712
11	213	22
12	245	24
13	148	855
14	106	4310

Fig. 5 Programmed Variable Loads.

finished smooth by grinding. The toes of welds at other details was left in as-welded condition.

The steels used in the tests for webs and flanges of the specimens were SM 50 YA and SM 50 A, respectively, the mechanical properties and chemical composition of which are given in Table 1.

(2) Variable amplitude loads

In this study, the variable waveform data to be used in tests were prepared by using computer simulation method. The simulation method of highway bridge loadings modelling of vehicles and the weight distribution of the each vehicle model were shown in Fig. 2. The traffic model used in this study was Type A in previous study[2].

The variable stress waveform was obtained by these simulations and the normalized stress range components histogram obtained by applying the rain-flow method to these variable stress are shown in Fig. 3.

The load waveform data prepared by simulations were recorded on floppy disks and these were digital-to-analog converted by personal computer, and then used as control signals for the testing machine.

In order to save time in the fatigue testing, the stress fluctuations below the 40 percent of the maximum value of stress in Fig. 3 shown previously were omitted. A part of the variable waveforms used in the tests

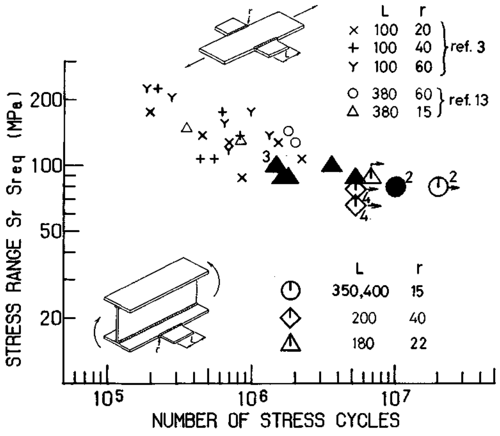


Fig. 6 Fatigue Test Results (Flange Gusset).


Photo 2 Fatigue crack in Flange Gusset Joint.

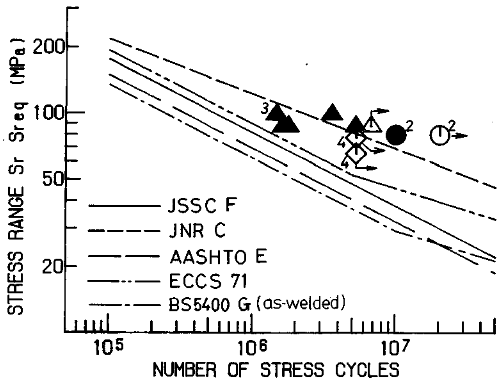


Fig. 7 Fatigue Test Results and Design Curves (Flange Gusset).

is shown in Fig. 4.

In fatigue tests of Specimens No. 1 and No. 2, the 14-stage variable loads (programmed variable loads) approximating the frequency distribution shown in Fig. 3 were used. The loading patterns of the programmed variable load are shown in Fig. 5.

The fatigue test were performed using an electrohydraulic servo fatigue testing machine of dynamic loading capacity 300 kN. The method of loading was four-point loading. A view of fatigue testing to be performed is shown in Photo 1. The load range in the fatigue test was such that the equivalent stress range in the bottom flange region would be approximately 100 MPa.

3. TEST RESULTS AND CONSIDERATIONS

(1) Flange gusset

Fatigue test results are shown in Fig. 6. Photo 2 shows a fatigue crack at the end of gusset with 350 mm in gusset length and 15 mm in fillet radius. This fatigue crack started from the corner of the gusset plate and grew into the flange plate. The initiation and growth behavior of fatigue cracks in other flange gusset details are almost same as this crack. The fatigue life in such case was the number of cycles of loading up to the repairing done with crack length at the flange surface between 7 and 28 mm.

The data under variable amplitude loads were arranged using the equivalent stress range S_{req} based on the Modified Miner Law.

$$S_{req}=(\sum S_{ri}^3 \cdot n_i / \sum n_i)^{1/3} \quad \cdots\cdots (1)$$

S_{ri} : i-th stress range (see Fig. 3 and Fig. 5), n_i : stress cycles of S_{ri}.

The figure also shows the results of fatigue tests carried out by the Japanese National Railways[3] and Honshu-Shikoku Bridge Authority[13]. All results other than those of the present experiments were obtained under loads of constant amplitude. As shown in the figure, it may be comprehended that fatigue strengths of gussets in girder specimens were considerably lower than the fatigue strengths of small specimens. This may be considered to have been due to the differences in gusset lengths, fillet radii and welding residual stress.

In Fig. 7, the design curves given for flange gussets in JNR[5], AASHTO[6], BS 5400[7], ECCS[8], and JSSC[9] are shown and compared with the test results of this study. The design curves of ECCS 71, AASHTO Category E and JSSC F are situated near the lower limits of the experimental results.

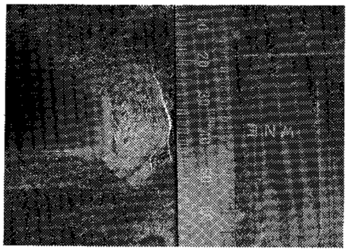


Photo 3 Fatigue Crack in Web Gusset Joint.

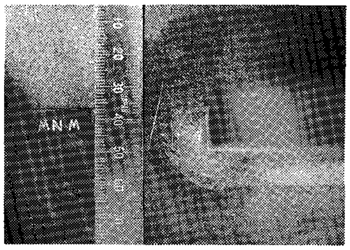


Photo 4 Fatigue Crack Propagated from Opposite Side (Web Gusset).

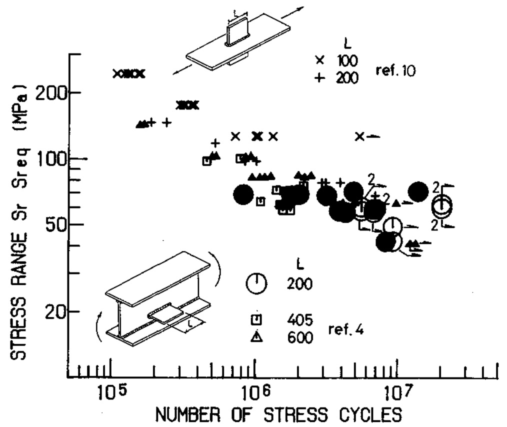


Fig. 8 Fatigue Test Results (Web Gusset).

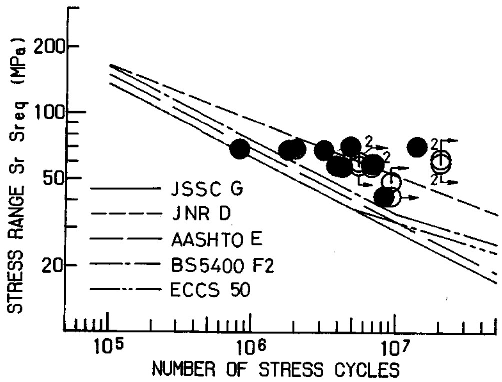


Fig. 9 Fatigue Test Results and Design Curves (Web Gusset).

However, this test result indicates that the design curve of JNR Class C is not conservative. This is because the design curve of JNR is based on the results of fatigue tests on small specimens. The design curve of BS 5400 code shown in Fig. 7 is for as-welded flange gussets. This code does not give the specified curve for flange gussets with fillets.

(2) Web gusset

The results of fatigue tests are shown in Fig. 8 and compared with results of other studies[4),10)]. Photo 3 shows the fatigue crack which started from the toe of a fillet weld and grew into a web. This fatigue crack penetrate through the web plate and appeared on the opposite surfaces as shown in Photo 4.

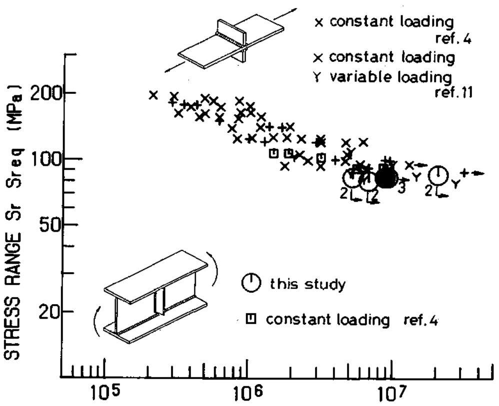


Fig. 10 Fatigue Test Results (Vertical Stiffener).

The fatigue life according to the results of these experiments were the numbers of cycles of loading when web-surface crack lengths became approximately 30 to 50 mm. As is clear from the figure, the fatigue strengths of web gussets in the girder specimens were considerably lower than those of small specimens.

The fatigue design curves of various codes for web gussets are shown in the Fig. 9. The design curve of ECCS 50 gives the lower limit of the results of the present experiments. With the design curves of BS 5400 F 2 and AASHTO Category E, the results are on the slightly short-life side of the design curve from among the test results on girder specimens. As for the JNR Class D design curve, it gives the lowest design curve in JNR code, but evaluates the test results of girder specimens on the fairly unsafe side.

(3) Vertical stiffener

The results of fatigue tests are given in Fig. 10. The condition of fatigue crack growth is shown in

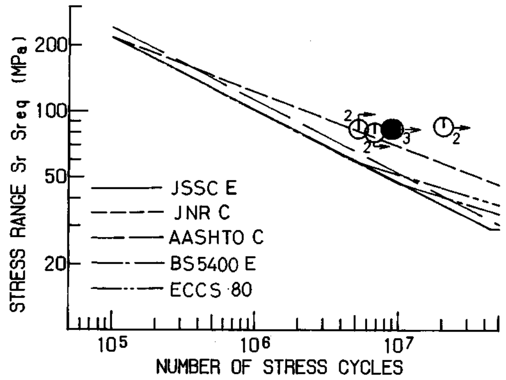


Fig. 11 Fatigue Test Results and Design Curves (Vertical Stiffener).

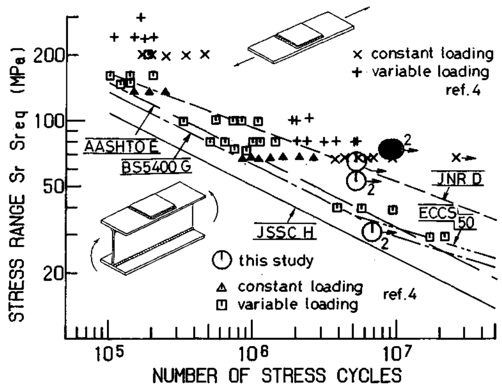


Fig. 12 Fatigue Test Results and Design Curves (Cover Plate).

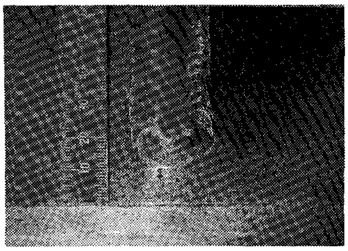


Photo 5 Fatigue Crack in Vertical Stiffener Joint.

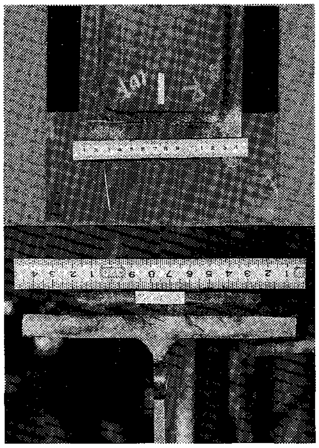


Photo 6 Fatigue Crack in Cover Plate Joint.

Photo 5. A fatigue crack initiated from the weld toe at the lower end of vertical stiffener and grew along the toe of fillet welds. The fatigue life of this joint is the number of cycles of loading when crack length reached approximately 30 mm. The results of fatigue tests of cruciform welded joint specimens by the authors[11] under the same variable stresses are plotted in the figure. As shown in the figure, the results of this study are slightly on the side of short life compared with the results of small specimens under the same variable load. However, differences in fatigue strengths of girder specimens and small specimens as prominent as in the cases of gusset joints were not found.

Test results of this study were compared with the design curves for the vertical stiffener detail in Fig. 11. The design curve of AASHTO Category C gives the lower limit of the test results. With the design curve of JNR Class C, the results produced are slightly on the short-life side among the test results for small specimens and girder specimens. The design curve of ECCS 80 is considerably on the conservative side compared with the experimental results.

(4) Cover plate

The cracking pattern is shown in Photo 6. As shown in the photograph, fatigue cracks initiated from two locations at the toes of cover plate welds, and they grew as semi-elliptical cracks.

The results of fatigue tests are shown in Fig. 12. The results of fatigue tests carried out by Fisher *et al.*[4] are also shown in the figure. The fatigue strengths of cover plates in this study were fairly high compared with the results of the girder specimens of Fisher *et al.* The design curve of JNR Class D gives the lower limit of experimental results for small specimens, but the evaluation is considerably on the unconservative side for experimental results with girder specimens.

4. REPAIR EFFECTS

Testing was interrupted when the fatigue cracks formed from weld toes at the various detail parts

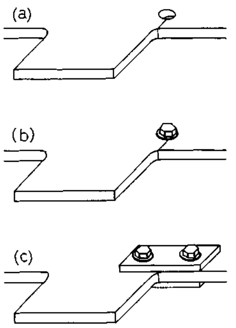


Fig. 13 Repair Method for Fatigue Crack.

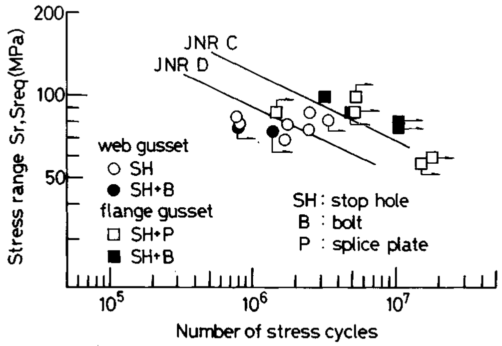


Fig. 14 Fatigue Test Results of Repaired Joints (Arranged by Nominal Stress Range).

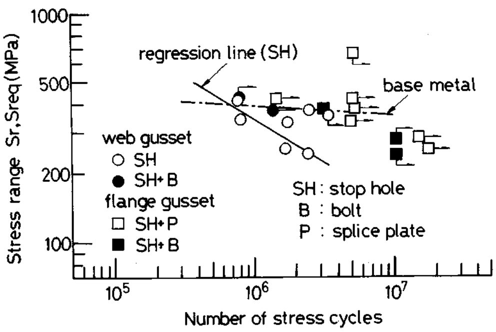


Fig. 15 Fatigue Test Results of Repaired Joints (Arranged by Modified Stress Range).

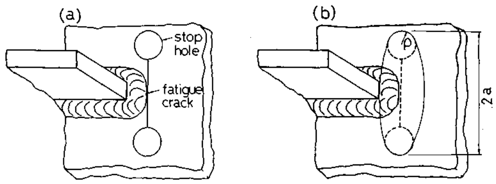


Fig. 16 Modelling of Stop Holes in Joints.

reached designated lengths, and repairs were made by the methods indicated below.

(a) Drill stop hole (Fig. 13(a))

(b) Tighten down on stop hole with high-strength bolt and nut (bolting) (Fig. 13(b))

(c) Drill stop hole and make a friction joint with high-strength bolt using splice plate (splicing) (Fig. 13(c))

The diameter of a stop hole was 18 mm and splice plates were 8 mm in thickness and 55 mm in width. Fatigue tests were resumed under completely the same conditions after repairing, and checks were made of crack re-initiation from the fringes of stop holes by visual inspection and the magnetic particle detection method.

The results of fatigue tests after repairing organized using the nominal stress range are shown in Fig. 14. The nominal stress range was that at the tips of holes. However, in case nominal stress ranges differed at the two ends of holes, the one of larger stress range was adopted. The figure also gives the design curves of JNR Class C and JNR Class D in order to show the degree of effect of repairs. The figure shows that in case of cracks initiated from flange gussets it may be said fatigue strength of JNR Class C can be expected when providing repairs consisting of tightening down stop holes with high-strength bolts and nuts. The effect of repairs will be even greater if splice plates were to be used. With regard to cracks formed from web gussets, they were formed at around 1 million cycles of loading. It should be considered that repair only by drilling of a stop hole is an emergency measure. It is thought that if a stop hole is tightened down by high-strength bolt there will be more repair effect than with a stop hole only.

The results of fatigue tests in case organization is done multiplying the nominal stress range by the stress concentration factor are shown in Fig. 15. As shown in Fig. 16(a), a stop hole drilled at the tip of a crack is considered as an elliptical cut-out such as Fig. 16(b), and the stress concentration factor of the stop hole is obtained by the following equation :

$$\alpha=1+2\sqrt{a/\rho} \quad \cdots\cdots (2)$$

a, ρ : see Fig. 16

In case nominal stress ranges differ for the two ends of the holes, the larger stress range is to be multiplied by the stress concentration factor. It should be added that the dot-dash curve in Fig. 15 indicates the results of fatigue tests on unnotched specimens of SM 50 steel[12].

As Fig. 15 shows, it may be said that strength of approximately the same degree as that of the unnotched specimen can be expected by performing repair of cracks formed from web gussets and flange gussets tightening down with high-strength bolts and nuts at stop holes. Furthermore, it is thought strengths about the same as or higher than the unnotched specimen can be expected by drilling stop holes and tightening down with splice plates for friction joints.

The solid line in the figure is a straight regression line obtained from the results of fatigue tests in case of providing repair with only stop holes for cracks formed from toes of welds at web gussets. It is thought that by using this straight line the effects of repairing with stop holes as emergency countermeasures to fatigue cracks can be examined.

5. CONCLUSION

The findings of this study are as follows :

(1) The fatigue strengths of welded joint in large-scale girder specimens are lower than fatigue strengths of small specimens. Especially, for web gussets and cover plates, there is a possibility of the results being on the hazardous side if evaluations are made using small specimens.

(2) Under variable load, cracks are formed from the toes of welds even when the equivalent stress range (RMC) falls below the fatigue limit under constant-amplitude loading. As for the results of fatigue strengths under variable load organized by equivalent stress range (RMC), they are on the straight regression line obtained from results under constant-amplitude loading or on the extension of that line.

(3) Of the fatigue design curves taken up in this study, there are curves that evaluate the experimental results of large-scale girder specimens on the unsafe side. Particularly, in evaluation of fatigue strength under variable load in the long-life range, it is thought there remains room for further study.

(4) By making repairs tightening down stop holes with high-strength bolts, strength of about the same degree as the basic material can be expected. Fatigue strengths will be improved further if splice plates are used.

In closing, it should be added that this study was made with a Grant-in Aid for Scientific Research from the Ministry of Education (General Research (C), Theme No. 01550362).

REFERENCES

1) Miki, C., Sakano, M., Tateishi, K. and Fukuoka, Y. : Data Base for Fatigue Cracking in Steel Bridges, Proceedings of JSCE, No. 392, pp. 403-410, 1988 (in Japanese).
2) Miki, C., Goto, Y., Yoshida, H. and Mori, T. : Computer Simulation Studies on the Fatigue Load and Fatigue Design of Highway Bridges, Proceedings of JSCE, No. 356, pp. 37-46, 1985.
3) Japan Society of Civil Engineers : Design Standard of National Railway Structures, Appendix 6, 1983 (in Japanese).
4) Keating, P. B. and Fisher, J. W. : Evaluation of Fatigue Tests and Design Criteria on Welded Details, NCHRP Report 286, 1986.
5) Japan Society of Civil Engineers : Design Standard of National Railway Structures, 1983 (in Japanese).
6) The American Association of State Highway and Transportation Officials : Standard Specification for Highway Bridges, 1977.
7) British Standards Institution : Steel, Concrete and Composite Bridges, Part 10, Code of Practice for Fatigue, BS 5400, 1980.
8) European Convention for Constructional Steelwork : Recommendations for the Fatigue Design of Steel Structures, 1985.
9) Japan Society of Steel Construction : JSSC Recommendations for Fatigue Design, 1989 (in Japanese).
10) Yamada, K., Mitsugi, Y. and Kondo, A. : Fatigue Strength of Gusset Welded to Tension Members and Allowable Stresses, Journal of Structural Engineering, Vol. 32 A, pp. 25-33, 1986 (in Japanese).

11) Miki, C., Murakoshi, J., Toyoda, Y. and Sakano, M. : Long Life Fatigue Behavior of Fillet Welded Joints under Computer Simulated Highway and Railroad Loading, Proceedings of JSCE, No. 404, pp. 63-70, 1988.

12) Miki, C., Nishimura, T., Tanabe, H. and Nishikawa, K. : Study on Estimation of Fatigue Strengths of Notched Steel Members, Proceedings of JSCE, No. 316, pp. 153-166, 1981.

13) Shimokawa, H., Takena, K., Itoh, F. and Miki, C. : Fatigue Strength of Large-Size Gusset Joints of 800 MPa Class Steels, Proceedings of JSCE, No. 356, pp. 279-287, 1985.

14) Fisher, J. W., Hausammann, H., Sullioan, M. D. and Pense, A. W. : Detection and Repair of Fatigue Damage in Welded Highway Bridges, NCHRP Report 206, 1979.

15) Yamada, K. and Kondo, A. : Fatigue Behavior of Repaired Members with Cracks, Proceedings of JSCE, No. 368, pp. 411-415, 1986.

(Received November 27 1989)