[PROC. OF JSCE No. 420/V-13 (Concrete Eng. and Pavements) August 1990]

EXPERIMENTS ON FATIGUE STRENGTH OF RC MODEL BEAMS UNDER A RUNNING LOAD

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Reinforced concrete simple beams without shear reinforcement were tested under a static load, a repeated load on a fixed point of a beam or a running load on a beam. The dimensions of the beams were 5 cm wide and 8 cm high. They had four variations of spans from 40 to 100 cm. A significant reduction of the fatigue strength was observed under a running load. A running load seemed to give wide or alternative stress amplitude to the beams and to give the beams more serious damage than the load on a fixed point.

Keywords : fatigue test, RC beam, running load

1. INTRODUCTION

The authors have been studying the fatigue strength of model RC-slabs of bridges. It has been known by the experiments that the fatigue strength of the slabs under a running load is far lower than that under a repeated load on a fixed point. These experiments showed the significant effect of the running load on the fatigue of structures. They wanted to understand the effect of the running load in detail and made simpler experiments of simple beams. The importance of the fatigue strength of beams under running loads has been recognized quite recently after the fatigue of slabs under the running load was studied[1]. A foretelling method for fatigue failure of beams was investigated in this experiment too.

2. MATERIAL AND SPECIMENS

(1) Microconcrete

The mix proportion of microconcrete was as shown in Table 1 the same as that for the model slab

Table 1 Microconcrete mix proportion.

W/C (%)	S/C (%)	Percentage of weight (%)			Max size of aggregate (mm)	Aggregate grading
		Water	Cement	Sand		
65	250	15.7	24.1	60.2	2.5	No prepared

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experiments published by the authors[2),3)]. This microconcrete was actually cement mortar. The maximum size of aggregate was 2.5 mm. High-early-strength-Portrand cement was used.

(2) Steel bar

The main reinforcements were deformed steel bars D 6, of which tensile strength and yield point were 55.3 and 40.1 kgf/mm², respectively. Stirrups located at the ends of the beams were 2 mm diameter annealed steel bars. Their yield strength was 25.8 kgf/mm² and the tensile strength was 33.1 kgf/mm².

(3) Beam dimension

Tested beam specimens were 5 cm wide, 8 cm high and 60, 80, 100 or 120 cm long as shown in Fig. 1. Steel ratio was 1.8 % as the effective depth was 70 mm.

(4) Casting and curing

A form for casting was made of plastic plates shown in Fig. 2. The beams were casted with being layed on their side. The bars were arranged in the form and then concrete was casted. Air bubbles were eliminated by vibrating the form. The beams were left 24 hours in the form and cured in water for ten days and then cured in the air for more than 28 days before experiments.

3. EXPERIMENT I—EXPERIMENT ON FOUR DIFFERENT SPAN LENGTHES

Beams of four different span lengthes were tested at the first stage to observe generally the fatigue behavior under the running load.

(1) Static test

Simple beams supported directly by the pins at the both ends were loaded through a wooden plate 3 cm width and 1.5 cm thick by 50 tons capacity Amslar machine. The tested results are summarized in Table 2. Material strengths for $\phi 5 \times 10$ cm cylinder are listed in Table 3. The coefficient of variations of the compressive strength and the tensile strength distributed from 5 % to 8 % for five specimens in each batch. Concrete casting was carried out for each span. In case of $a/d>2$ and the shear failure in Table 2, calculated shear strengths by Okamura and Higai[5)] agreed well with tested results. The average ratio of calculated to tested shear strengths was 1.11 and the coefficient of variation was 2.7 %.

Cracking processes are shown in Fig. 3 (a) to 3 (d). For all spans vertical flexural cracks initiated under the load and diagonal crack developed later on one side of beams. Fractures took place along the diagonal cracks which developed finally between the load and the nearer support except SC-1, SC-2 and SD-1 specimens. The deflection of the tested beams tended to increase suddenly near the failure. This showed that brittle shear fracture of beams developed abruptly. SC-1, SC-2 and SD-1 specimens indicated flexural failures.

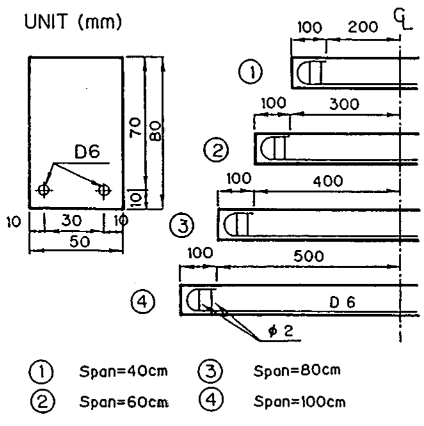

Fig. 1 Dimensions and bar arrangements of the beams.

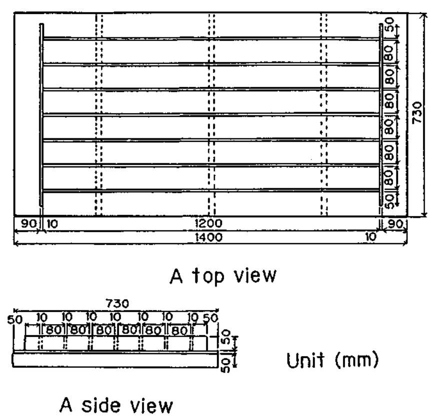

Fig. 2 Form for casting.

Table 2 Static test in Experiment I.

Span length (cm)	Specimen	Loading from the support (cm)	Ultimate load (kgf)
40	SA-1	20	1151
	SA-2	10	851
	SA-3	10	1960
	SA-4	10	1075
60	SB-1	30	1084
	SB-2	20	936
	SB-3	10	1240
80	SC-1	40	895
	SC-2	40	946
	SC-3	20	888
100	SD-1	50	765

Table 3 Material strength for each beam.

Span length (cm)	Compressive strength (kgf/cm²)	Tensile strength (kgf/cm²)
40	368	47.1
60	388	34.9
80	481	41.7
100	453	42.1

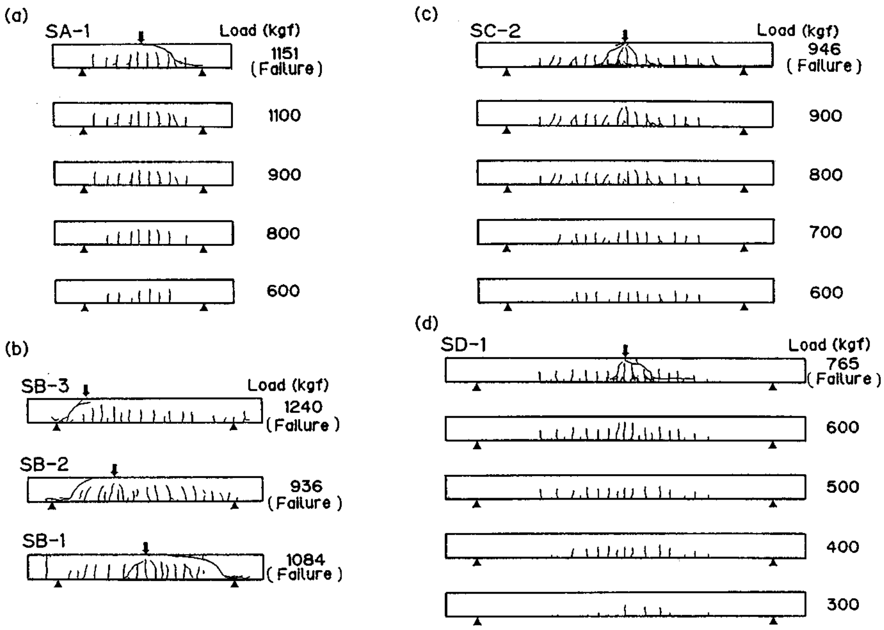

Fig. 3 Crack of beams in static test.

(2) Running load test

a) Running load test machine

The simple beams were set on a movable bed, which was drived back and forth by a air piston (Fig. 4) 15 times in one minute. The load was applied on a beam between both supports through a caster by a weight and lever. The caster had a steel wheel with solid rubber tire and an article put on the market[2]. The supporting condition was hinged-hinged in order to fix the beam on the bed.

b) Results and discussion

Tested results are summarized in Table 4. The load ratio was a ratio of the running load to the standard strength of beams calculated by Okamura and Higai's equation[5]. When beams failed under the running load, the distances from the support to a top of dominating diagonal crack were $2d$ to $3d$. Therefore, 2.5 of a/d was assumed for calculations. All failures were due to shear as shown in Fig. 5 to 8.

These results were remarkably lower than the fatigue strength under a repeated load on a fixed point as to be mentioned in the following (3). This shows significance of the running load test for design of bridges.

Processes of crack development were almost in the same way for all four kinds of spans. The flexural

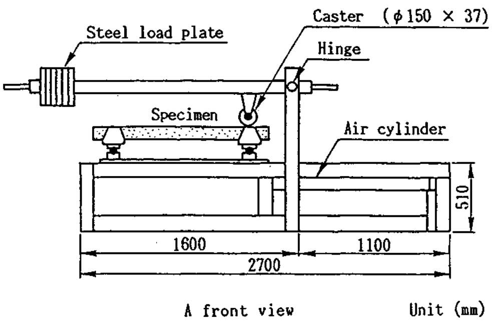

Fig. 4 Running load test machine.

Table 4 Running load in Experiment I.

Span length (cm)	Specimen	Running load (kgf)	Load ratio	Cycles to failure
40	MA-1	600	0.477	2996
	MA-2	550	0.438	64236
	MA-3	593	0.472	1452
60	MB-1	600	0.591	796
	MB-2	550	0.541	1658
	MB-3	500	0.492	104532
	MB-4	500	0.492	36506
	MB-5	450	0.443	138444
80	MC-1	600	0.606	1192
	MC-2	550	0.556	498
	MC-3	500	0.505	42114
	MC-4	475	0.480	159038
	MC-5	525	0.531	30442
100	MD-1	500	0.544	1082
	MD-2	400	0.435	305978
	MD-3	450	0.490	61402

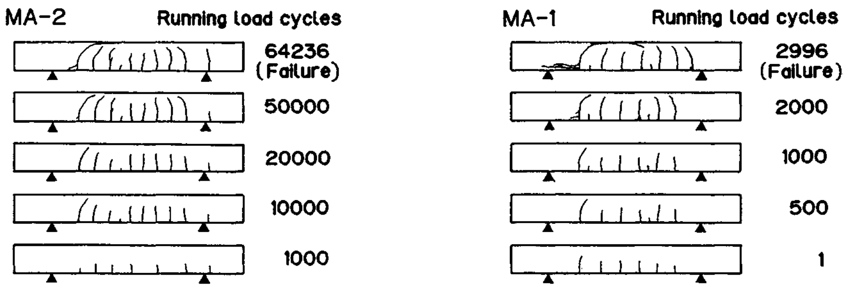

Fig. 5 Crack development under a running load (MA specimens).

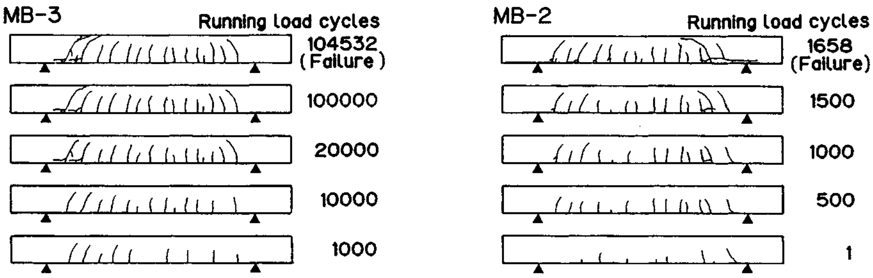

Fig. 6 Crack development under a running load (MB specimens).

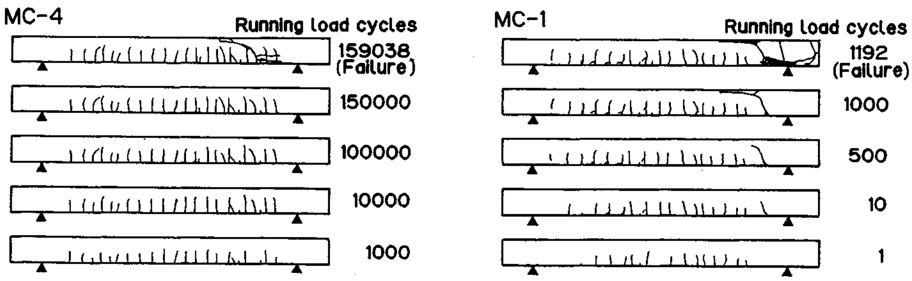

Fig. 7 Crack development under a running load (MC specimens).

cracks grew to diagonal cracks and the cracks came to the upper surface finally. The fatal fracture cracks were of arch shape. Cracks along the main reinforcement of MB-3 specimen seemed to indicate bond fatigue damage. Under the running load it may be guessed that bond stress amplitude will become wider or alternate. When a beam had a stable long period of fatigue process in which diagonal cracks developed

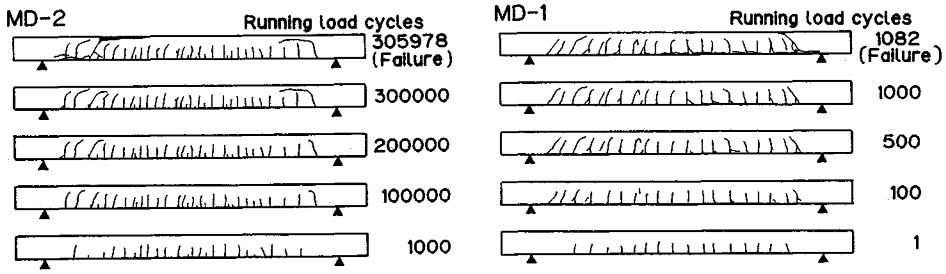

Fig. 8 Crack development under a running load (MD specimens).

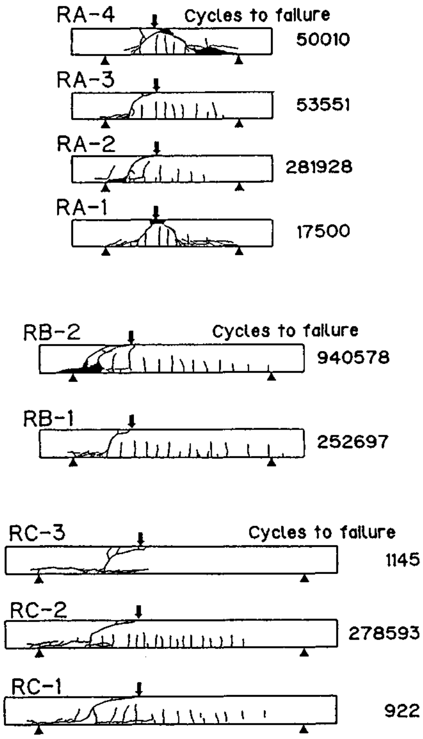

Fig. 9 Crack development at failure under a repeated load on a fixed point.

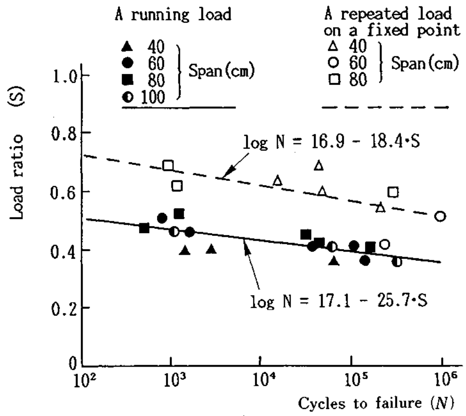

Fig. 10 Fatigue strength under a running load and a repeated load on a fixed point.

Table 5 Repeated load on a fixed point in Experiment I.

Span length (cm)	Specimen	Limit load (kgf)		Loading from the support (cm)	Upper load ratio	Cycles to failure
		Upper	Lower			
40	RA-1 RA-2 RA-3 RA-4	860 750 810 920	100	15	0.710 0.619 0.668 0.759	17500 281928 53551 50010
60	RB-1 RB-2	500 600	100	18	0.492 0.591	252697 940578
80	RC-1 RC-2 RC-3	780 685 710	100	30	0.767 0.674 0.698	922 278593 1145

slowly, it had a long life.

(3) Repeated load on a fixed point

Although many experiments were reported for fatigue strength of beams under a repeated load on a fixed point[4)-6)], almost none was known about the relations between the fatigue of beams under running load and that under repeated load on a fixed point.

a) Test method

The load was applied on the point of the beams for 40 cm and 60 cm span lengths where the fatigue failure took place under the running load. It was assumed that the running load run on the top of the dominating diagonal crack, when the beam failed. So the loading points were different for the beams with different span length. The load was applied by the fatigue machine at the rate of 4 Hz. The supporting condition was the same as for the static tests.

b) Results and discussion

Beams failed as shown in Fig. 9. The flexural cracks initiated and they developed into diagonal cracks.

Results of Table 5 are shown in Fig. 10 with S-N curves derived by the least square method.

4. EXPERIMENT II—EXPERIMENT ON SIMPLE BEAMS OF 80 cm SPAN

In this experiment 80 cm span beams were tested concentrically. The authors tried to derive a more accurate S-N curve by the statistical procedure and observed fatigue process in detail by measuring beams' deflection. If there is no description, the test method was the same as in Experiment I.

(1) Static test

The load was applied on the beams by the caster which was used for the test under the running load. The supporting condition was the same as for the static test of Experiment I.

The tested results are summarized in Table 6. The compressive strength of all static test specimens was 340 kgf/cm². Calculated shear strengths by Okamura and Higai[5] agreed well with tested results. The average ratio of calculated results to tested shear strengths was 1.03 and the coefficient of variation was 7.8 %. The calculated shear strength by Okamura and Higai[5] was chosen for the standard strength of beams for fatigue tests as same as Experiment I.

(2) Running load test

The deflections were measured by noncontact displacement sensor by using eddy current effect. Twenty to thirty thousands cycles were carried in a day. If the test had to be carried over to the next day, it was started again earlier than 12 hours after it had been halted.

a) Fatigue strength

Table 7 summarizes the results. The results in the table are arranged in order of small number of life cycles. The survival rate p in Table 7 was calculated by the following

$$p=1-r/(n+1) \quad (1)$$

where p is the ratio for the beam with r-th shorter life among n specimens tested under the same load level.

If the fatigue life follows the logarithmic-normal distribution as same as concrete[3], the statistical distribution of the test results of life is

$$t=A\cdot\log N+B \quad (2)$$

where t is a deviation from the symmetrical axis of normal distribution and is derived for given p from the normal integration table[7]. For the average life $\overline{N}$, $t=0$ for $p=0.5$ is put into the formula. Then $\overline{N}$ is

$$\log \overline{N}=-B/A \text{ or } \overline{N}=10^{-B/A} \quad (3)$$

The tested results are plotted on logarithmic-normal probability paper as shown in Fig. 11. The three lines for previous three load levels are almost parallel. A remarkable reduction of fatigue life is observed by very small increment of load level.

Table 6 Static test in Experiment II.

Specimen	Loading from the support (cm)	Ultimate load (kgf)
sa-1	40	1003
sa-2		939
sa-3		988
sb-1	30	1000
sb-2		889
sb-3		865
sc-1	25	903
sc-2		917
sd-1	20	875
sd-2		741
sd-3		914
sd-4		750

Table 7 Running load test Experiment II.

Specimen	Running load (kgf)	Compressive strength (kgf/cm²)	Load ratio	Cycles to failure	Survival rate p (%)
ma-1	475	400	0.51	65466	66.7
ma-2		400		137832	33.3
mb-1	500	388	0.54	8524	83.3
mb-2		400		20270	66.7
mb-3		400		30390	50.0
mb-4		388		32640	33.3
mb-5		395		62512	16.7
mc-1	525	400	0.56	5778	80.0
mc-2		400		7444	60.0
mc-3		388		11738	40.0
mc-4		400		33510	20.0
md-1	550	315	0.64	812	——
me-1	600	315	0.70	170	——

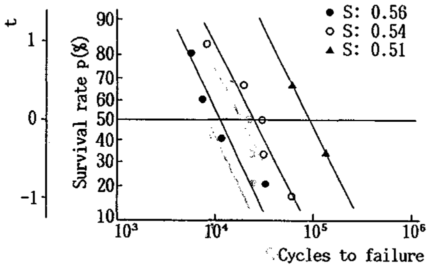

Fig. 11 Survival rate depending on magnitude of a running load.

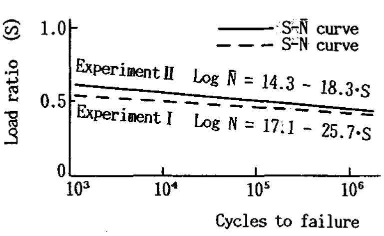

Fig. 12 S-$\overline{N}$ in Experiment II and S-N in Experiment I.

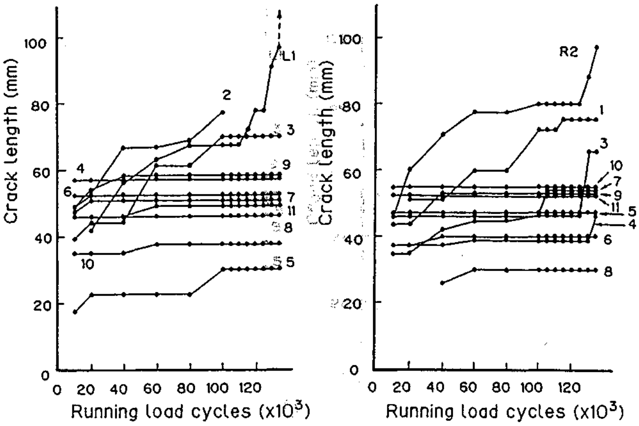

Fig. 13 Development of crack under a running load. L1, L2, ···, R1, R2, ··· denote the numbers in Fig. 14.

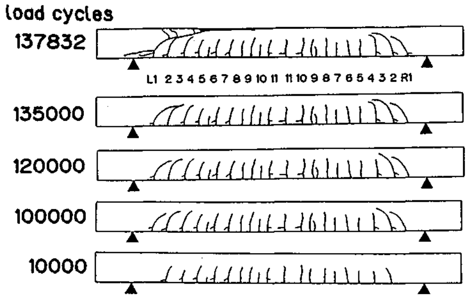

Fig. 14 Crack patterns under a running load.

In Fig. 12 S-$\overline{N}$ relation is presented in a solid line as well as S-N of Experiment I in a dotted line. They are similar. However as shown in p-N relation of Fig. 11 the fatigue life scatters widely and then it may be considered that application of S-N relation to design is very complicate.

b) Observation of cracks

Development of cracks are shown in Fig. 13 of which abscissa indicates number of load cycle and axis of ordinate indicates length of cracks. Crack patterns are shown in Fig. 14. In these figures it is observed that flexural crack initiates and it develops to diagonal crack and at last it reaches to the upper surface and a beam collapses. There is one dominating crack on each side of span. Flexural cracks around the center of span do not develop seriously, however cracks near supports develop consistently. For a long process of fatigue, growth of crack length does not concentrate on certain cracks but most cracks develop together. The dicisive crack developed quickly only in the last stage of fatigue life.

When observing dominating cracks at which fractures took place, the relations between their lengths and load cycles are summarized in Fig. 15. Abscissa of the figure indicates the percentage of load cycle to failure cycle of each beam. The dominating cracks seem to grow rapidly from around 80 % of cycles to failure mostly in the tests.

c) Deflection

Increase of the deflection seems to correspond to the growth of the dominating cracks (Fig. 16). When the test was suspended at night, the residual deflection decreased during the test suspension but it recovered to original line of cycle-deflection once the tests resumed. The deflections of the beams were total deflection including the elastic and the plastic deflections.

(3) Repeated load on a fixed point

Test machine was the same as in Experiment I. The load was applied at the rate of 4 Hz at the distance

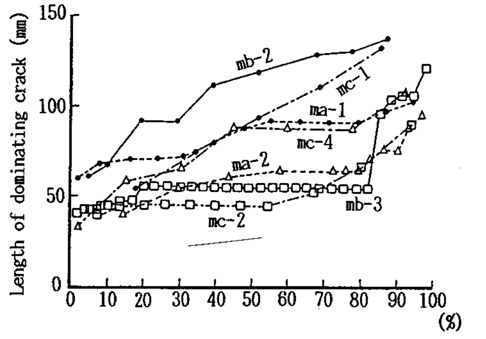

Fig. 15 Growth of dominating crack.

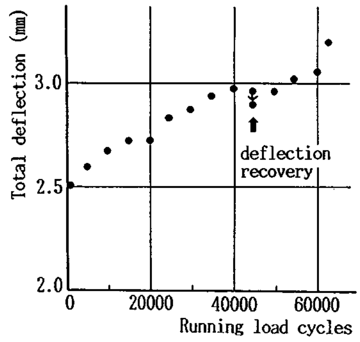

Fig. 16 Deflection of ma-1 under a running load.

Table 8 Repeated load on a fixed point.

Specimen	Limit load (kgf)		Upper load ratio	Cycles to failure
	Upper	Lower		
ra-1	775	100	0.84	96677
rb-1 rb-2 rb-3 rb-4	800	100	0.87	642 4208 5920 98664
rc-1 rc-2	825	100	0.90	43 348
rd-1	850	100	0.93	631

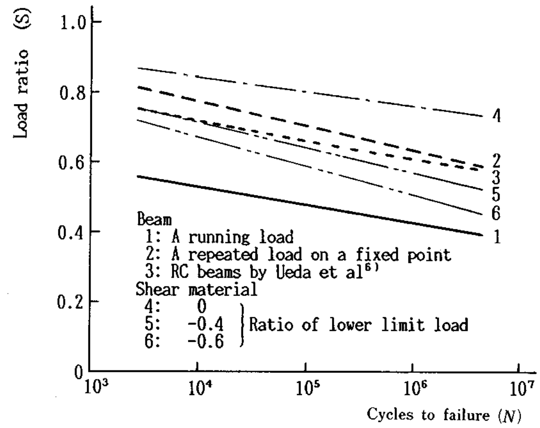

Fig. 17 S-N relations of beams and microconcrete.

25 cm from the support where almost all fatigue failure took place under the running load. Tested results are tabled in Table 8.

Cracking process in this test was almost the same as for running load. Deflection did not increase in this test so much as in running load test. Even near the failure sharp increase of deflection was not observed.

5. CONCLUDING REMARKS

(1) S-N curve

S-N curves by combining Experiment I and II are summarized in Fig. 17 with microconcrete fatigue strength[3]. It is observed that the fatigue strength of beams decreases remarkably by running a load. This reduction seems to suggest that the alternative stress induced by transfering a load should have a significant role in the reduction when material fatigue characteristics are compared with the fatigue strength of beams.

(2) Prediction of fatigue failure

Cycles to fatigue failure of beams distributes so widely that it is almost impossible to predict the fatigue life of each beam through S-N curve. It was observed in the experiments that cracks and total deflection grew fast near fatigue failure. This fast growth of cracks and deflection took place at around 80 % of fatigue life, then the following simple formula for prediction of the fatigue life may be derived once the fast growth of cracks be observed:

$$Y = X + 0.2\,X \qquad (4)$$

where Y denotes fatigue life and X denotes load cycles at which fast growth of cracks and deflection are observed.

ACKNOWLEDGEMENT

This experiments owed to the hard work done by undergraduate students of Department of Transportation Civil Engineering, Nihon University, under the authors' instructions for their graduation thesis works. The students were Mr. Kooichi Sato (Nihonkouzo Engineering Co.) and Mr. Daisuke Terai (Sumikou Consultant Co.) in 1987, Mr. Kooji Suzuki (Aoki Construction Co.) and Mr. Osamu Takahashi (Tohoku Denryoku Co.) in 1988. The authors would like to show the deepest thanks to their contribution. The running load machine was designed by Mr. V. R. Macam, Jr. and produced by Iwata-seisakujo Co. Mr. Kooichi Ono contributed to complete the manuscript.

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(Received August 4 1989)