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DEVELOPMENT OF A NEW FATIGUE TESTING MACHINE FOR HIGH FREQUENCY FATIGUE DAMAGE ASSESSMENT

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ABSTRACT

A new simple fatigue testing machine, which can carry out fast and low-cost fatigue tests of welded joints subject to wave with high frequency vibration, has been developed. This machine is designed for plate bending type fatigue tests, and wave load is applied by using motors with eccentric mass. Springing vibration is superimposed by attaching an additional vibrator to the test specimen, and whipping vibration is superimposed by an intermittent hammering.

Fatigue tests which simulate springing and whipping by a conventional servo-type fatigue testing machines are very expensive and use a large amount of electricity. If one uses these conventional machines, it is difficult to simulate superimposed stress wave forms at high speed, and it takes long hours of testing to examine the high frequency effect. In contrast, it is found that fatigue tests can be carried out in fast, i.e. waves with 10Hz or higher frequency for out-of-plane gusset welded joint specimens with 12mm plate thickness by using the developed machine. The electricity to be used for fatigue tests could be minimal, for example one thousandth of that needed for conventional machines. These results demonstrate the superiority of the developed machine.

1. INTRODUCTION

In recent years, the size of container ships has increased. This triggered a discussion about the effect of the hydro-elastic response called “springing” and “whipping” with regards to fatigue strength.

Sumi [1] and Kitamura et al. [2] investigated the fatigue crack propagation behaviors under variable amplitude loading with different frequency components. They reported that the smaller amplitude component of higher frequency superimposed on the larger amplitude component of lower frequency has not significant effect on the fatigue damage, but only the enlargement effect of the total amplitudes of superimposed stress is effective. Fricke and Paetzold [3] reported similar findings, and proposed to count only the enlarged wave load cycles. However, it is not clear whether their statements are valid in practical fatigue assessment of ship structures because the number of fatigue tests of their study is limited. It is needed to develop a high frequency fatigue damage assessment method for welded structures by carrying out numerous fatigue tests under various wave loading cases with high frequency vibration.

Conventional fatigue testing machines of closed loop system are widely used for fatigue tests of welded joints and members. The initial and running costs of these machines are very high. The running cost and testing time jump to unacceptable level when wave loads with high frequency vibration are simulated.

In this study, new simple fatigue testing machines, which can carry out fast and low-cost fatigue tests of welded joints subject to high frequency vibration superimposed wave loading, are developed. The superiority of the developed machines, the drastic reduction of testing time and running cost, is demonstrated by carrying out fatigue tests under springing superimposed wave loading.

2. FATIGUE TESTING MACHINES USING MOTORS WITH ECCENTRIC MASS

Yamada [4] developed simple fatigue testing machines using commercially available motors with eccentric mass, and they were applied to various fatigue tests. First, fatigue testing machines for plate bending type of loading were developed. They showed that fatigue tests could be carried out in relatively fast, i.e. 20 Hz, for specimens with various thickness and sizes. The electricity to be used for the fatigue tests could be minimal, for example one thousandth of that needed for the conventional servo-type fatigue testing machine. Normally a plate of 12mm thick were used to simplify the tests, but, plates with 6~19mm thick were also tested.

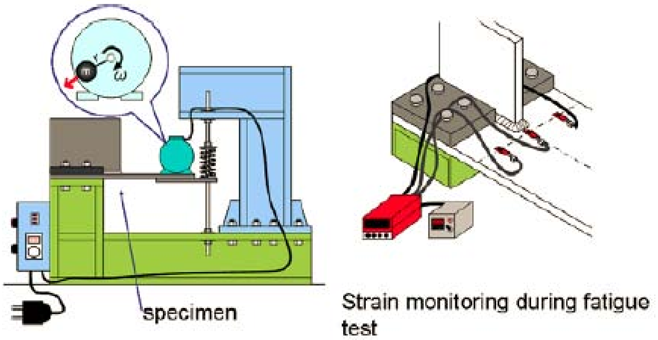

Fig. 1 Plate Bending Vibration (PBV) type fatigue testing machine.

The fatigue testing machine for plate bending is shown in Fig. 1. It consists of a frame to support test specimen, a motor with eccentric mass attached to the specimens, control system for the motor, and spring system. Hereafter, this machine is called 'Plate Bending Vibration (PBV) type testing machine'. The system does not have a load control system, and the strain amplitude during fatigue test is monitored by strain gages attached to specimens. Mean stress can be controlled by the spring system. If the spring is push down, a tensile mean stress can be applied to the upper side of the specimen. Table 1 shows an example of comparison of the running costs of conventional and PBV-type testing machines. In this case, the electricity expense per specimen is about 650USD for conventional machine and 0.60USD for PBV-type machine. The minimum testing time of PBV-type machine is shorter than 1/10~1/6 of that of a conventional machine.

Table 1 An example of running costs of PBV-type and conventional testing machines.

	Conventional machine	Develped machine
Power source	Hydraulic pressure	Electric motor
Load application	Load, Displacement	Inertia force
Load frequency	about 2~3Hz	20 Hz
Electricity expense per specimen	65,000JPY (650USD)	60JPY (0.60USD)

The bending vibration of the specimen is not restrained in PBV-type machines, while the specimen's vibration cannot be generated in conventional machines because the displacement is restrained by actuators. Therefore, for PBV-type machines, springing vibration can be superimposed onto the Low Frequency Wave (LFW) load by attaching an additional vibrator with higher rotation frequency to the test specimen. Frequencies of LFW and springing loads can be controlled individually. In the same manner as springing, whipping vibration can be superimposed onto LFW by intermittent hammering. In this case, the frequency of the LFW can be determined freely while that of the whipping vibration is confined to the bending natural frequency (BNF) of the test specimen.

3. APPARATUSES FOR HIGH FREQUENCY EFFECT TESTS

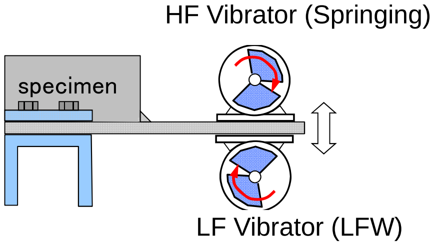

Fig. 2 Schematic view of a springing load generation system.

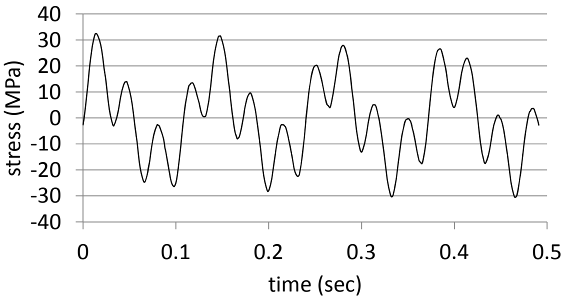

Fig. 3 An example of a waveform with springing vibration.

3.1 Springing superimposed wave loading

A springing vibration is induced by attaching an additional vibrator (motor with eccentric mass) to the specimen. Fig. 2 illustrates the schematic view of the apparatus. The frequencies of LFW and springing can be controlled individually. The amplitudes are controlled by changing the unbalancedness of eccentric masses. The amplitude can also be controlled by changing the vibrators' position.

Let T_{HF}, ω_{HF} and $\Delta\sigma_{HF}$ be the period, angular frequency and nominal stress range induced by springing vibration, and T_{LF}, ω_{LF} and $\Delta\sigma_{LF}$ be those of LFW. An example of the stress history generated by the springing superimposed wave loading is shown in Fig. 3. In this case, ω_{HF}/ω_{LF} is 3.78 and $\Delta\sigma_{HF/}\ \Delta\sigma_{LF}=0.74$.

In this study, the fatigue strength of test specimens is assessed by using two cycle counting methods: LFW counting and envelope counting. In the former method, the springing vibration is neglected, and it is assumed that the equivalent amplitude and period of the waveform are those of LFW. In the latter, the stress history is modeled by an envelope of the superimposed waveform. In this case, the equivalent stress amplitude becomes the peak-to-peak value of the envelope, but the period, T_{env}, is the same as that of LFW.

3.2 Whipping superimposed wave loading

Toyoda et al. [5] reported that the characteristics of whipping response can be modeled as follows: 1) the frequency of whipping-induced vibration is 5 times higher than that of LFW; 2) the whipping fades away within 5 LFW. In this study, a testing apparatus which can generate this stress waveform is developed.

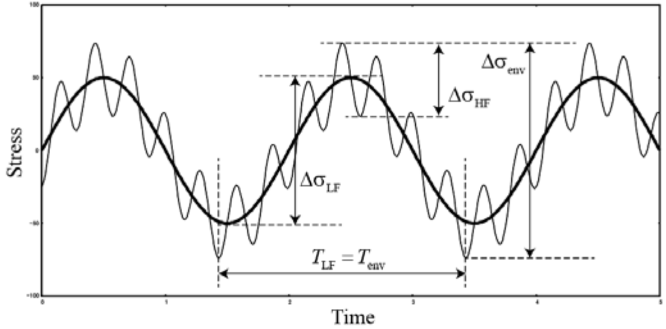

Fig. 4 Definitions of cycle counting parameters of springing superimposed waveform.

Fig. 5 The hammering apparatus.

A whipping vibration is induced by hitting the end of the test specimen by a rotary hammer. The hammer hits the specimen once in every 5 cycles of LFW. The location of the eccentric mass is detected by using an encoder attached to the vibrator's rotation shaft, and the hammer is controlled so that it hits the specimen at the time when the eccentric weight is placed at the specified position. This makes the phase difference between whipping and LFW vibrations remain unchanged. Fig. 5 shows the photo of the apparatus.

The frequency of whipping vibration equals the BNF of the specimen. The impact load intensity and damping can be controlled by changing the hammer head weight and the polymer vibration insulator inserted between the specimen and the support spring. The LFW frequency is chosen so that it becomes 1/4~1/5 of BNF. Fig. 6 shows an example of stress waveform generated in a specimen with 12mm plate thickness. In this case, BNF is 28Hz, and LFW frequency is 7Hz. This figure shows that the developed apparatus can generate intended waveforms.

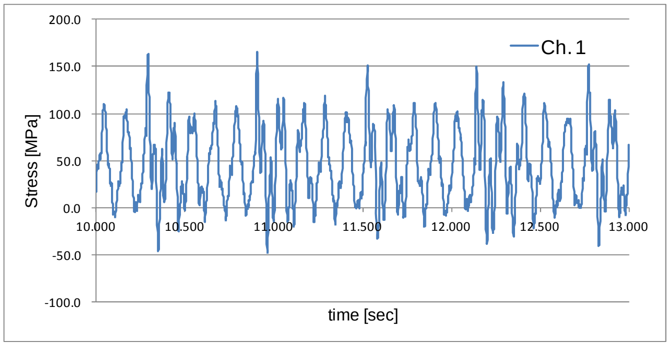

Fig. 6 An example of stress waveform with whipping vibration.

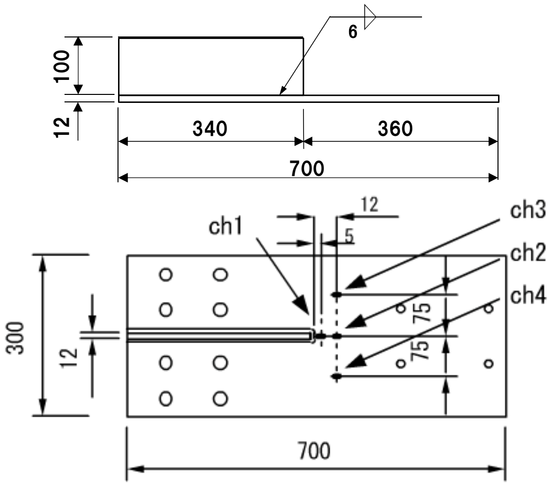

Fig. 7 Out-of-plane gusset welded joint specimen (unit:mm).

4. FATIGUE TEST RESULTS

Fatigue tests were carried out for out-of-plane gusset welded joint specimens made from AH32 ship structural steel plates. Size and shape of specimens are shown in Fig. 7. The left end of a specimen were fixed onto the frame base while the free end was excited by one or two motors with eccentric mass. The motor's rotation frequencies were maintained at constant during each test.

Fatigue cracks initiate at the weld toe near the main plate's centerline. The crack propagates along the weld bead during a certain period, then turns and propagates into the main plate. Let N_b be the number of load cycles at which the crack propagation path turns into the main plate. Plate surface strains were measured at 4 strain gages. Gages were arranged at points ch1~4 in Fig. 7. Ch1 and Ch2 are in the vicinity of the hot spot (crack initiation point), and their responses include the local stress concentration due to the weld. Responses of Ch3 and Ch4 are not affected by the local stress concentration, and they can be treated as the nominal bending strains at the hot spot.

4.1 Constant amplitude loading tests

Constant amplitude fatigue tests were carried out by using PBV-type machines in Japan Marine United (JMU) Technical Research Center and Osaka University. Fig. 8 shows an example of time histories of measured strain amplitudes. All strains show nearly constant amplitudes for a certain period. Then, strains affected by the local stress concentration (Ch1 and Ch2) decrease substantially with cycles while nominal strains (Ch3 and Ch4) increase slightly. These changes are due to the stress redistribution caused by the fatigue crack propagation. Therefore, the nominal bending stress range, $\Delta\sigma$, is determined from the initial strain amplitudes of Ch3 and/or Ch4. In this test, the Nb determined by visual inspection was about 8.53 x 10^5 cycles, and Ch1 strain amplitude decreased to 35% (65% drop) of its initial amplitude at this cycle. The Ch1 strain amplitude showed about 65% drop at Nb in all constant amplitude tests carried out by JMU and Osaka University.

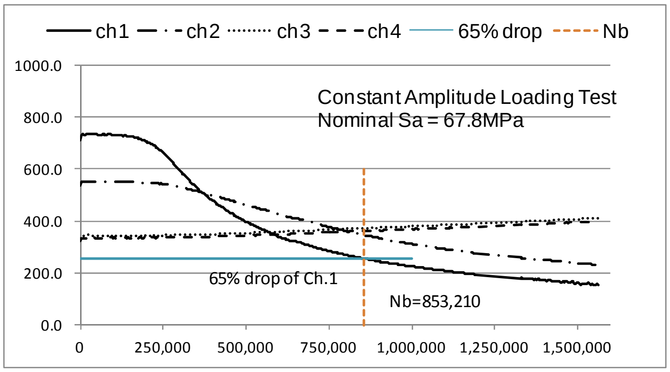

Fig. 8 Changes in strain amplitudes during a constant amplitude fatigue test (Osaka Univ., Sa=67.8MPa).

Nagoya University (Ishikawa et, al [6]) carried out fatigue tests under almost the same conditions as those of this study. In their tests, specimen's size and shape are the same, but specimens were made of SM490 steel. The relationship between the nominal stress range $\Delta\sigma$ and N_b examined in these tests are shown in Fig. 9. The regression curve of Nagoya University's data is also plotted in this figure. This figure shows that fatigue strength of PBV-type specimens examined by three institutes are almost equivalent, and the fatigue strength can be represented by the regression curve of Nagoya University's data when fatigue lives are defined by Nb.

4.2 Springing superimposed wave loading tests

Springing superimposed wave loading tests were carried out in JMU Technical Research Center by using a PBV-type testing machine with additional vibrator shown in Fig 10. The loading conditions chosen are shown in Table 2. The prefixes of condition names "S1", "S2" and "S3" show the intended $\Delta\sigma_{LF}$ (36MPa, 48MPa and 60MPa). $\Delta\sigma_{HF}/\Delta\sigma_{LF}$ and/or $\Delta\sigma_{HF}/\Delta\sigma_{env}$ indicate the relative intensity of springing component.

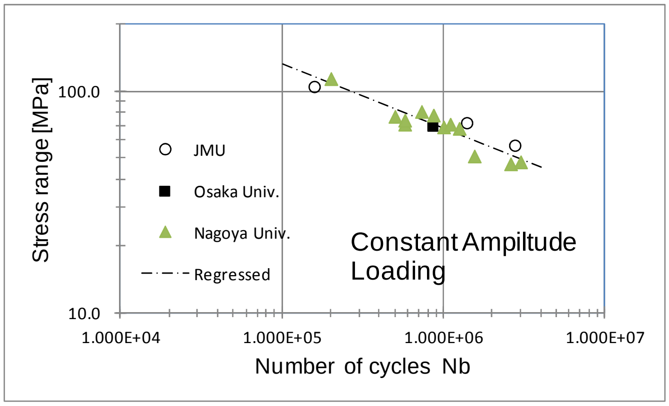

Fig. 9 Fatigue strength of out-of-plane gusset welded joints under constant amplitude loadings (the relationship between nominal stress range and Nb).

Table 2 Loading conditions and test results of springing superimposed wave loading tests.

No.	ω_{HF}/ω_{LF}	$\Delta\sigma_{LF}$	$\Delta\sigma_{HF}$	$\Delta\sigma_{env}$	$\Delta\sigma_{HF}/\Delta\sigma_{LF}$	$\Delta\sigma_{HF}/\Delta\sigma_{env}$	Nb
S1-1	3.78	36.7	27.0	63.0	0.74	0.43	1.885E+06
S1-2	3.78	35.6	33.6	69.4	0.94	0.48	7.210E+05
S1-3	3.78	35.6	44.7	80.7	1.25	0.55	2.220E+05
S2-1	3.78	47.6	28.0	78.7	0.59	0.36	4.925E+05
S2-2	3.78	48.0	36.5	87.7	0.76	0.42	4.260E+05
S2-3	3.78	47.8	55.2	106.9	1.16	0.52	1.525E+05
S3-1	3.82	60.1	21.4	84.6	0.36	0.25	4.860E+05

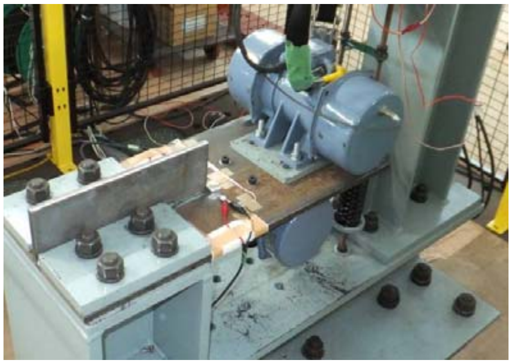

Fig. 10 The PBV-type testing machine with additional vibrator used in the springing superimposed wave loading tests.

The measured fatigue lives (Nb) are shown in Table 2. It is shown that the fatigue life becomes shorter with $\Delta\sigma_{HF}$ if $\Delta\sigma_{LF}$ remains unchanged. The S-N diagram based on $\Delta\sigma_{LF}$ is shown in Fig. 11. Under the conditions chosen, the regression curve of Nagoya University's data, which represents constant amplitude test results well, leads to non-conservative estimates for springing superimposed loading cases if the fatigue life is estimated by using LFW counting method. The S-N diagram based on $\Delta\sigma_{env}$ is shown in Fig. 12. This figure shows that the measured data for springing cases are within the variability range of constant amplitude test results if the fatigue life is estimated by envelope counting method.

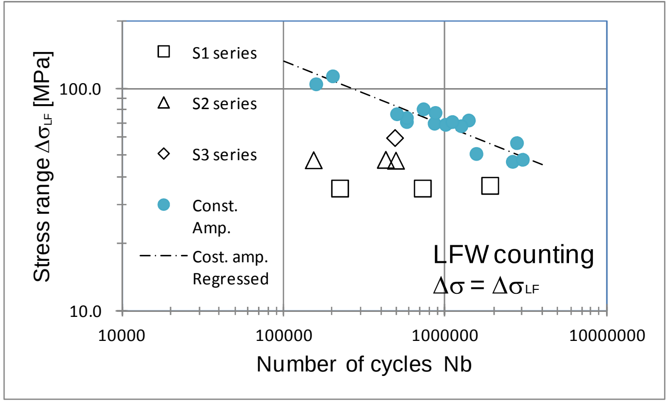

Fig. 11 Fatigue strength of out-of-plane gusset welded joints under springing superimposed wave loading assessed by LFW counting method.

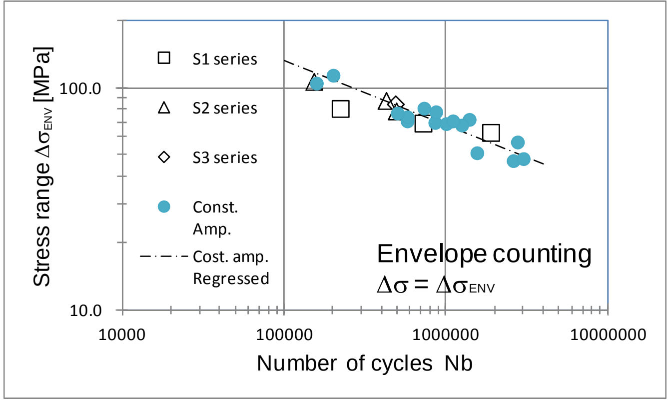

Fig. 12 Fatigue strength of out-of-plane gusset welded joints under springing superimposed wave loading assessed by envelope counting method.

It is needed to note that the above results were obtained from only a few test data, and it is unclear whether similar results can be found in the generality of cases. Further investigation is needed to develop a high frequency fatigue damage assessment method for welded structures, and it is necessary to carry out numerous fatigue tests under various wave loading cases with high frequency vibration. For springing fatigue tests carried out in this study, the total testing time was about 5 days, and the total electricity expense was only about 250JPY (2.5USD). This superiority of the developed machines, the drastic reduction of testing time and the remarkable economic efficiency, will contribute to the promotion of research works on high frequency fatigue damage assessment method.

5. CONCLUSIONS

New simple fatigue testing machines, which can carry out fast and low-cost fatigue tests of welded joints subject to high frequency vibration superimposed wave loading, were developed. The superiority of the developed machines, the drastic reduction of testing time and running cost, was demonstrated by carrying out fatigue tests under springing superimposed wave loading.

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