Transactions of the 15th International Conference on
Structural Mechanics in Reactor Technology (SMiRT-15)
Seoul, Korea, August 15-20, 1999

Vertical Seismic Response of Overhead Crane

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ABSTRACT

Vertical seismic excitation is considered as an important seismic design issue in Japan. Equipment unrestrained vertically may resonate and its response is significantly magnified under vertical seismic excitation. Overhead crane is a example of equipment that is unrestrained vertically.

The dynamic behavior of an 150-ton-capacity overhead crane under vertical seismic excitation was investigated by scale model excitation test and non-linear time history analysis. The excitation tests were performed with several input level and the vertical response with each input level was obtained. The results of analysis approximately corresponded to the results of excitation test.

INTRODUCTION

In design standards for overhead crane, only ASME NOG-1 is considering the vertical seismic force as a design dynamic load. Other design standards do not consider seismic load in the vertical direction at all or they consider as a static seismic load. The seismic design method which can evaluate dynamic vertical seismic load is studied in Japan.

Overhead crane is one of the equipment which is not restrained vertically, and the natural frequency is comparatively low. There is significant meaning to clarify the vibration characteristic in the vertical direction of overhead crane. This study focused on clarifying the vertical seismic response of overhead crane. An 1/8 scale model was used for the excitation tests and a simulation analysis were performed in this study.

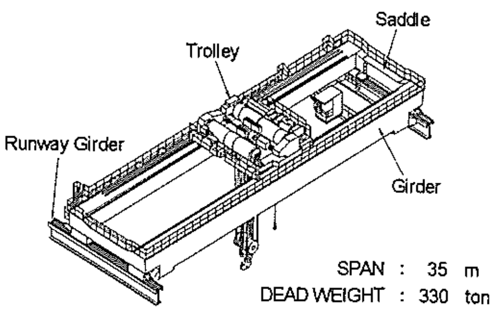


Fig. 1 TYPICAL 150TON OVERHEAD CRANE

TYPICAL OVERHEAD CRANE

An overhead crane of the rated load 150ton, the overall length 35 m and total weight 330 ton was selected as a study object. The configuration of the overhead crane is shown in Figure 1. The overhead crane consists of two girders, two saddles to connect them, a trolley moving to the longitudinal direction of the overhead crane and wheels. The driving-device is installed in the one of two girders. The overhead crane is supported vertically by two rails on the two runway girders installed in the building.

The vertical vibration modes of the crane are shown in Figure 2. The vertical natural frequency of the crane varies from about 3 to 5 Hz with the location of the trolley, and the crane can be regarded as a soft structure in the vertical direction, comparatively.

SEISMIC WAVE

A floor response wave based on an artificial earthquake wave was used as an input seismic wave to obtain the vertical seismic response of the overhead crane. The floor response wave is the vertical wave at the floor level where overhead crane is installed. The floor response wave and response spectrum are shown in Figure 3.

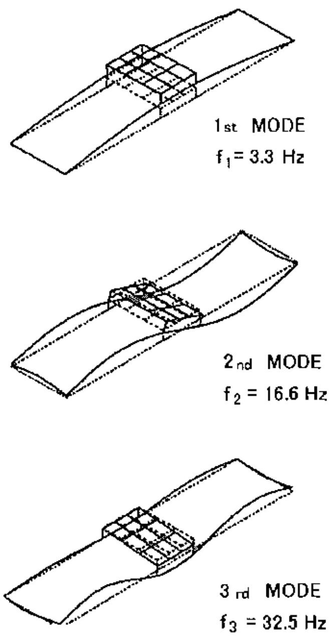
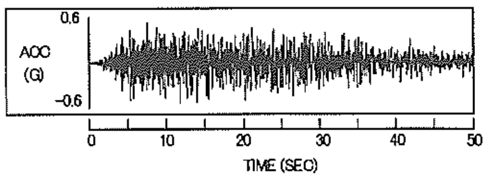
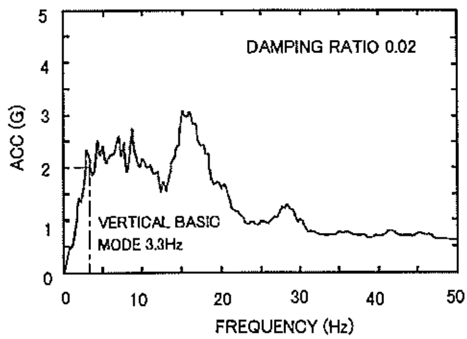


Fig. 2 VERTICAL VIBRATION MODE



Floor Response Wave



Response Spectrum

Fig. 3 SEISMIC WAVE

SCALE MODEL EXCITATION TEST

Test Model

The appearance of the test model and the vibration characteristic value of the test model are shown in Photograph 1 and Table 1 respectively. This test model was scaled by using a similarity law shown in Table 2. To study the vertical seismic response of the overhead crane, the relation between the acceleration of gravity and crane response acceleration is important. The ratios of parameters in the similarity law were set up so that acceleration of the actual overhead crane was the same as the test model. The acceleration ratio was 1.0 by letting dimension and time change according to this similarity law. This similarity law premised that Young's modulus of the test model was equal to that of the actual overhead crane. Even though the only dimension was reduced, the mass of the test model did not agree with the value by the similarity law. Therefore, lead weights were put in the test model for the mass adjustment.

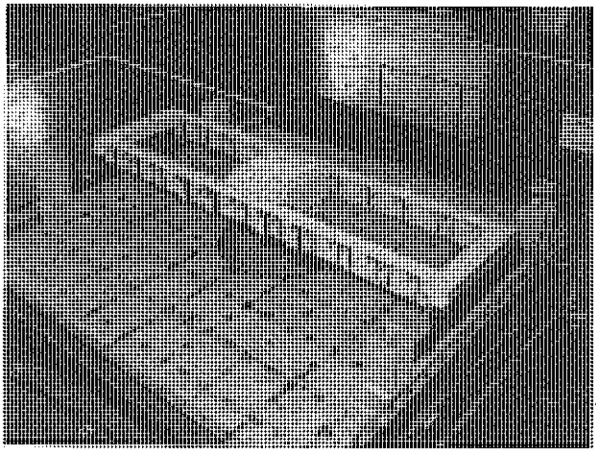


Photo. 1 1/8 SCALE TEST MODEL

Tab. 1 THE VIBRATION CHARACTERISTICS OF THE TEST MODEL

CHARACTERISTICS		ACTUAL CRANE	TEST MODEL
GIRDER MASS (ton)	DRIVE SIDE	94	1.47
	NON-DRIVE SIDE	81	1.27
TROLLEY MASS (ton)		85	1.33
SADDLE MASS (ton)		38	0.59
CRANE SPAN (m)		35	4.36
SECTION AREA OF GIRDERS (m^2)		0.18	0.0046
MOMENT OF INERTIA OF AREA (m^4)	HORIZONTAL	0.076	0.000018
	VERTICAL	0.16	0.000039
NATURAL FREQUENCY (Hz)	VERTICAL (Basic Mode)	3.3	9.7

Tab. 2 SIMILARITY LAW

PARAMETERS		SCALE
LENGTH	$L_a / L_m = N$	8
ACCELERATION	$A_a / A_m = N / X^2$	1
TIME	$t_a / t_m = X$	$\sqrt{8}$
FREQUENCY	$f_a / f_m = 1 / X$	$1 / \sqrt{8}$
YOUNG'S MODULUS	$E_a / E_m = 1$	1
SPRING CONSTANT	$K_a / K_m = N$	8
MASS	$M_a / M_m = N X^2$	64
FORCE	$F_a / F_m = N^2$	64

* subscript a : Actual Crane
m : Test Model

Testing Condition

In the excitation test for 1/8 scale model, time was shortened according to similarity law by the floor response wave shown in the preceding paragraph. Actually, the time scale of the input wave was shortened to $1/\sqrt{8}$ times. The same acceleration response as the actual overhead crane was simulated in the test model by using the shortened input wave according to the similarity law.

The maximum acceleration amplitude of the input wave was set up as the input level to investigate the relationship between the vertical seismic response. All excitation tests were performed by 3- D shaking table in Yokohama research institute of IHI.

Measurement

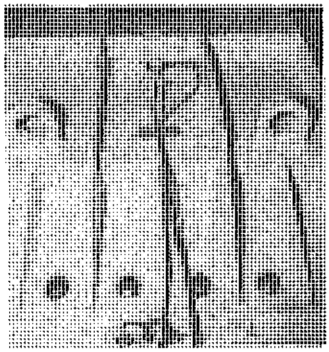
The following data were measured in order to clarify the response behavior of the overhead crane under large vertical seismic input:

- Input acceleration at shaking table
- Response acceleration at the center of a trolley
- Response acceleration at girder
- Reaction force at wheel
- Upward displacement at saddle

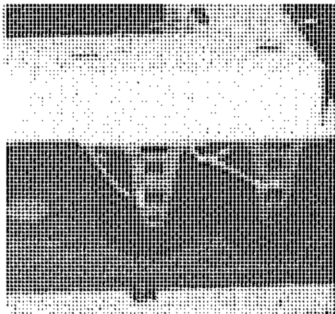
Sensors were installed as shown in Photograph 2. Strain gages were attached on the fixed metal fittings of wheels, and the strain signals were converted into the reaction force at each wheel. As for the conversion between the strain signal and the reaction force, the relation was obtained by the calibration test performed before the excitation test. The upward displacements on both saddles were measured by eddy current type gap sensors installed between the saddle and rail. All the data was recorded with the sampling time 0.001sec after processing with analog low pass filter 300 Hz.

Test Result

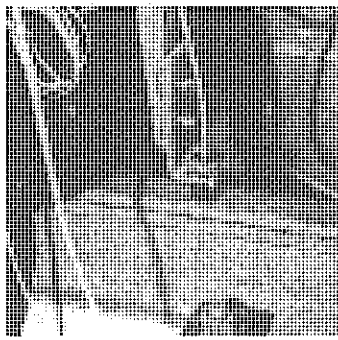
The response acceleration at the center of the trolley, the upward displacement at each saddle and the reaction force at each wheel were evaluated by comparing with the input level. The relationship between the excitation level and the upward displacement of saddle part is shown in Figure 4. And relationship between the excitation level and the response acceleration at the center of trolley is shown



Accelerometer on Trolley
at the End of Saddle



Strain Gage at Each Wheel



Gap Sensor

Photo. 2 SENSORS FOR THE MESUREMENT

in Figure 5. When the response acceleration of the center of the trolley becomes larger than about 1.8 G, the increase rate of the response acceleration becomes larger than that in the smaller region, and the relation is regarded as bi-linear. This inclination is similar with the upward displacement growing as shown in Figure 4. It can be said that a change of vibration behavior of the model was caused by the impact after the leap of the test model, because the input level of upward displacement occurring almost agrees with the input level of the response acceleration changing.

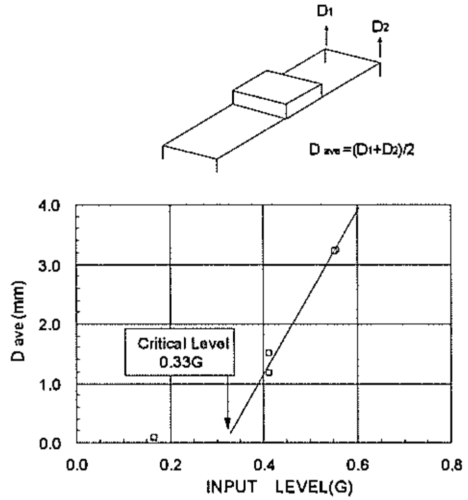


Fig. 4 UPWARD DISPLACEMENT AT SADDLE

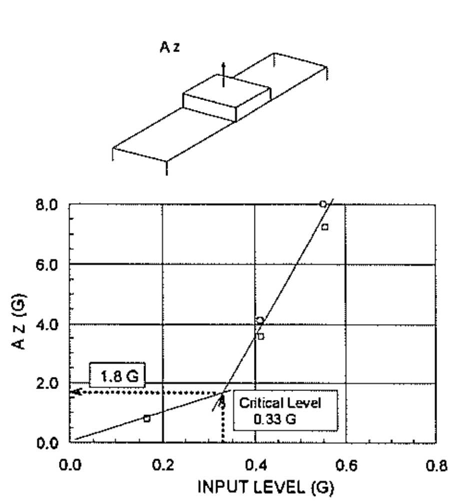


Fig. 5 ACCELERATION AT THE CENTER OF TROLLEY

When the growth of the upward displacement of the saddle is defined as the occurrence of the overhead crane leap, the critical response acceleration that overhead crane begins to leap can be estimated as shown in Figure 5. The Critical response acceleration estimated from Figure 4 and 5 is 1.8 G. This critical value is almost equal to the acceleration obtained by the following equation. It is suggested that the existence of leap of the overhead crane can be predicted and evaluated by this equation.

$$\alpha_{cr} = \frac{M}{m_{eq}} \cdot g \quad (1)$$

α_{cr} : Critical acceleration
M : Total mass of overhead crane
m_{eq} : Effective mass of the 1st vertical vibration mode

The relation of the reaction force at wheel and the excitation level is shown in Figure 6. The reaction force in this figure means the total load in four wheels installed in the saddle. The reaction force at wheels increases almost linearly with the increase of the excitation level. In the reaction force at wheels, the remarkable change of the inclination as response acceleration did not appear. It is recognized that the collision did not effect much to the wheel reaction force as compare with the response acceleration. The straight line shown in Figure 6 is the wheel reaction force provided by the response spectrum analysis. By comparing the plot points of the test results and the straight line, it is obvious that the wheel reaction force can be predicted by linear analysis with an adequate margin.

The summary of the test results are as follows:

- When the vertical response acceleration of overhead crane exceeds the critical response acceleration, the leap of overhead crane occurs. The critical response acceleration is obtained by the acceleration of gravity multiplied by the ratio of the effective mass and the total mass of overhead crane.
- The relationship between the wheel reaction force and the excitation level is almost linear. It is recommended that the adequate margin will be taken in the wheel reaction force obtained by linear analysis. About 30% margin is recommended.

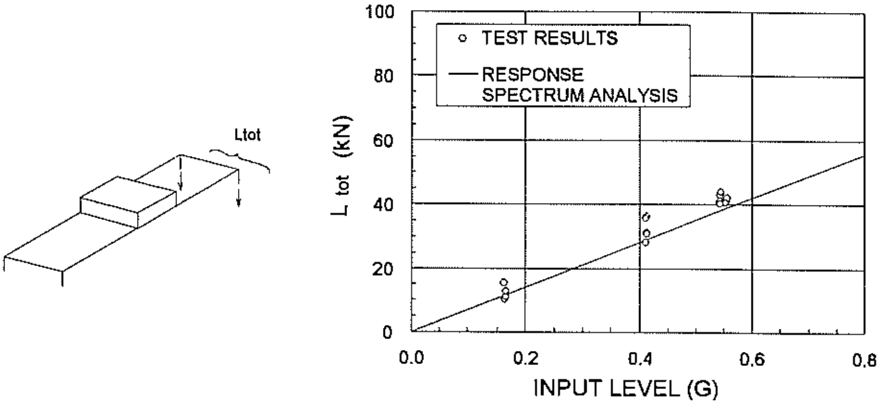


Fig. 6 THE REACTION FORCE AT WHEELS

SIMULATION ANALYSIS

In the preceding test results, it was shown that the response force of the overhead crane with large vertical seismic could be estimated by linear analysis. For the purpose of studying the vertical seismic response of overhead cane in detail, the simulation analysis was performed.

Nonlinear Analysis Model

The model with gap elements at wheel part as shown in Figure 7 was used to simulate the nonlinear phenomenon accompanying with leaping under the large vertical seismic

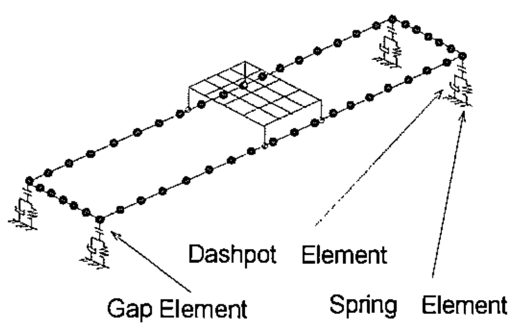


Fig. 7 NONLINEAR ANALYSIS MODEL

input.

A parallel combination of a spring and a dash pot were arranged with each gap element in series. Elasticity and energy absorption at wheel part were modeled by these elements. The damping coefficient of a dash pot was decided so that the coefficient of restitution in wheel part was 0.8.

The damping of the whole crane was given as Rayleigh damping so that damping ratio of the fundamental vertical vibration mode was 2 %.

Analysis Method

A time history analysis by the direct integral method was performed using a finite element analysis program ABAQUS Ver.5.6. The initial value of the time step was set up in 0.001sec, and the automatic time step function was utilized.

Analysis result

The upward displacement and the reaction force at wheels obtained by analysis are shown in Figure 8 and Figure 9 respectively. In the upward displacement with both results of the test and the analysis, a remarkable leap was observed in three times. The values of the displacements by analysis are almost equal to test results. Peaks of the reaction force at wheel appeared with the peaks of upward displacement at the same time. Accurately, the reaction force peaks at the moment when the displacement becomes zero after the peak of the upward displacement. This means that the peak of the reaction force at wheel appears at the moment of the wheel contacting after the leap.

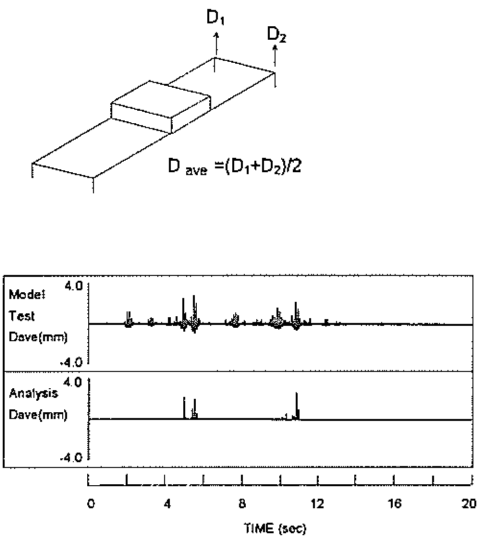


Fig. 8 THE UPWARD DISPLACEMENT AT SADDLE

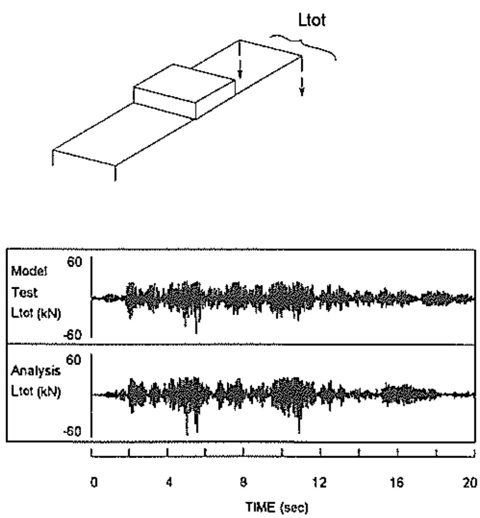


Fig. 9 THE REACTION FORCE AT WHEELS

CONCLUSION

In this study, the vertical seismic response of typical 150 ton overhead crane was investigated by the 1/8 scale model excitation test and the simulation analysis. For predicting the overhead crane to leap, a simple equation for the prediction was confirmed by the excitation test and suggested.

It was confirmed by the test that the reaction force at wheels could be estimated by the linear analysis though the collision appeared after the leap of overhead crane. It is concluded that the several margin (about 30% recommended) is needed to evaluate the reaction force at wheels in the design of the overhead crane if the leap of overhead crane is predicted. The simulation analysis using the nonlinear model with gap elements was carried out. The upward displacement and the reaction force at wheels provided by the analysis almost agreed with the test results.

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