RESULTS OF VIBRATION TESTS ON TALL BUILDINGS AND THEIR EARTHQUAKE RESPONSE

by

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SYNOPSIS

The vibration tests using shaking machine were carried out on 18 tall buildings and their natural periods and damping coefficients were investigated. From these results, the relation between fundamental natural period and stories, fundamental natural period and 2nd one, fundamental natural period and 3rd one, each natural period and fraction of critical damping and others were obtained.

On the other hand, the observations of dynamic behavior during the regional earthquakes were performed on 11 tall buildings to obtain their natural periods, distribution of maximum acceleration of each building and so on. From the acceleration records of these buildings, the authers tried to estimate fraction of critical damping of each building.

INTRODUCTION

The objective of the vibration tests on buildings is to recognize the appropriateness of building design and to get the useful data for seismic design of other buildings in the future.

A lot of useful data have been stored by the vibration tests before the completion of the buildings. At present, after the completion of the buildings, the earthquake observations are being carried out on not less than 10 buildings. The building response amplitudes observed during earthquakes are smaller than the design values analyzed by the dynamic response of strong motion, but are far larger than the examined values by vibration tests.

In view of the above facts, it is very important and will be useful to clarify the difference between the design values and the results of vibration test and earthquake observation.

VIBRATION TEST

The authors have carried out the forced vibration tests on 18 tall buildings and the microtremors were observed on 4 tall buildings. Table.1 shows the results of the vibration tests on 11 tall buildings with a summary of certain important building characteristics where the earthquake observations are now being carried out.

The outline of the discussion about the dynamic characteristics of these tall buildings made clear by means of the vibration tests is as follows:

(1) As shown in Fig.1, the relation between fundamental natural period T_1(sec) and stories above ground N can be expressed as follows:

$$T_1 = (0.06 \sim 0.10) N \qquad (S)$$

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$T_1 = (0.03 \sim 0.06)\ N$ (RC , SRC)

where (S) denotes steel frame structure, (RC) reinforced concrete structure and (SRC) reinforced concrete steel composite frame structure respectively.

(2) The relation between T_1 and eaves height H (m) is obtained as follows:

$T_1 = (0.018 \sim 0.028)\ H$ (S)
$T_1 = (0.010 \sim 0.018)\ H$ (RC , SRC)

(3) Fig.2 shows the relation between fundamental natural period T_1 and 2nd T_2, 3rd T_3 (sec) ones. It makes little differrence between (S) and (RC, SRC). The following relation is obtained:

$T_2 = (0.3 \sim 0.4)\ T_1$ when averaged $T_2 = 0.33\ T_1$
$T_3 = (0.15 \sim 0.25)\ T_1$ $T_3 = 0.19\ T_1$

(4) The relation between fundamental natural period of transverse or longitudinal direction T_1 (sec) and fundamental torsional natural period T_T (sec) can be obtained as follows:

$T_T = (0.06 \sim 1.0)\ T_1$ and average is $T_T = 0.8\ T_1$

(5) Fig.3 presents the relation between each modal natural period and its damping coefficient h (%) on each building in each direction. Damping coefficients obtained from the vibration tests are given by:

$h = 0.5 \sim 2$ (S)
$h = 1.5 \sim 6$ (RC , SRC)

The larger the values of T_1 are, the less the values of h are. The higher order damping coefficients from these data are not so large as to prove that the assumption of internal viscous damping holds good.

EARTHQUAKE OBSERVATION

The earthquake observations are being carried out on 11 tall buildings located in Tokyo and Yokohama where the vibration tests were carried out before completion. Fig.4 presents their building sites and seismographs locations. Twenty-one earthquakes that occurred from 1968 to 1974 in these areas, ranging from II to IV in the Japanese Seismic Intensity scale (J.M.A.), are summarized in Fig.5 with their epicenters, dates and J.M.A.. The authors discuss about the data obtained from those earthquakes.

Relation between the intensity scale and the acceleration level is as follows:

Intensity scale (J.M.A.)	II	III	IV	V
Acceleration level (gals)	2.5 - 8	8 - 25	25 - 80	80 - 250

The main results obtained directly from the time-histories of recorded seismic waves are pointed out in brief as follows:

(1) The vertical distribution of the maximum amplitude of acceleration in the building is presented in Fig.6, which shows that the maximum values of acceleration were not necessarily observed on the tops of tall buildings.

(2) The amplitude of acceleration where fundamental natural period is predominant is calculated from the recorded seismic waves on the top of the building. The calculated values are 10 to 50 times larger than the amplitude of acceleration by the vibration tests.

(3) As is indicated in Fig.7, the relation between fundamental natural period T_{1E} (sec) obtained from the vibration tests and fundamental natural period T_{1N} (sec) observed during earthquakes or the relation between fundamental natural period T_{1D} (sec) calculated in structural design and T_{1N} is expressed as follows:

$$T_{1N} / T_{1E} = 1.13$$
$$T_{1N} / T_{1D} = 1.01$$

The maximum acceleration level of most of the earthquake records is less than 30 gals on the base of each building, but some of the fundamental natural periods observed are comparatively close to the designed ones.

(4) Buildings vibrate by earthquakes in every order natural period. An evidently simple and predominant wave foam was chosen from the earthquake acceleration records of the building in which the maximum amplitude of acceleration occurred, and its period is named "the main period". The relation between this main period and observed fundamental natural period is shown in Fig.8. The buildings having a short natural period vibrated principally in their lower order natural periods; on the contrary, the buildings having a long natural period were mainly in motion in their higher order natural periods.

Next, in order to seize accurately the 2nd and 3rd natural periods during earthquakes, the authors computed the Fourier spectra of the seismic waves recorded at the base and the top of each building and calculated their transfer functions. The Fourier amplitude spectra and the transfer functions were smoothed by using the Hanning window.

(5) These results obtained from the transefer functions are added in Table.1, which shows that each natural period during earthquakes is comparatively close to the designed one.

(6) Each modal damping coefficient was estimated from the peak value of the transfer function. The relation between each modal natural period and its damping coefficient of each building is presented in Fig.9, where the damping coefficients of 2nd and 3rd modal numbers obtained are slightly larger than the examined ones. On the other hand, the estimated fundamental damping coefficient is large as compared with the examined one. One of the reasons considered is that the time-domain analyzed is not so long as to estimate the fundamental damping coefficient.

CONCLUSION

(1) Each modal natural period during earthquakes is smaller than or equall to the designed one, and is larger than that obtained by the vibration tests.

(2) The maximum values of acceleration are not necessarily observed on the top floor in the case of tall building. Building having a longer natural period shows a tendency to vibrate in its higher order natural periods.

(3) The value of the 2nd modal damping coefficient obtained by the vibration tests is larger than that of the fundermental one, and is smaller than or equall to that of the 3rd one. The values of damping coefficients of buildings of steel frame are smaller than those of buildings of reinforced concrete and reinforced concrete steel composite frame.

(4) In regard to the buildings of steel frame, the values of the 2nd and the 3rd modal damping coefficients during earthquakes are apt to be larger than those obtained by the vibration tests, besides the value of fundamental damping coefficient by earthquakes is remarkably larger than the one by vibration tests.

A lot of utilized data concerning with vibration tests and earthquake observations have been discussed in this paper. However the dynamic characteristics during earthquakes should be continuously investigated for further developement.

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They also wish to express their thanks to the owners of those buildings and the persons concerned with.

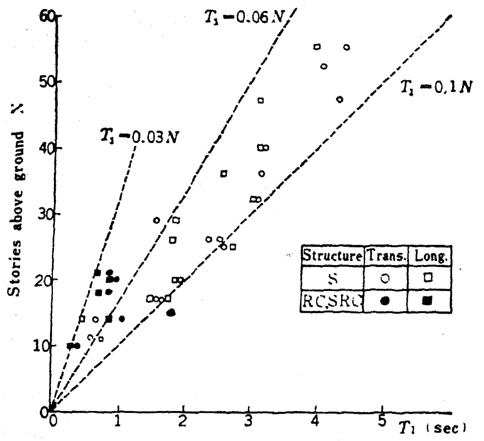


Fig. 1 Relationship between 1st Natural Period and Stories on Vibration Tests

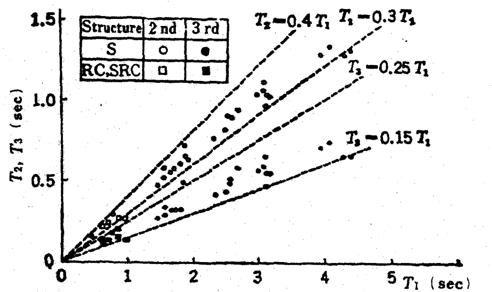


Fig. 2 Relationship between 1st Natural Period and 2nd, 3rd Ones on Vibration Tests

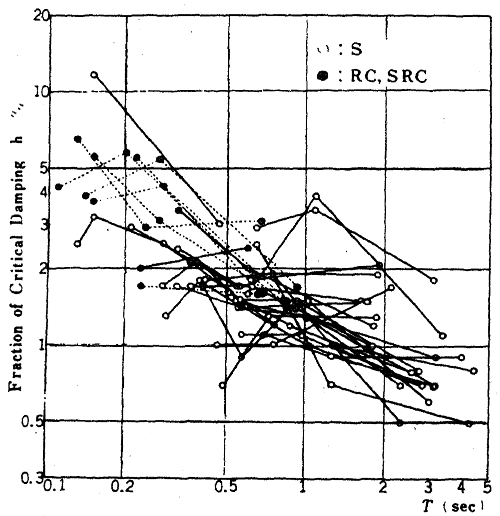


Fig. 3 Relationship between Each Natural period and Fraction of Critical Damping

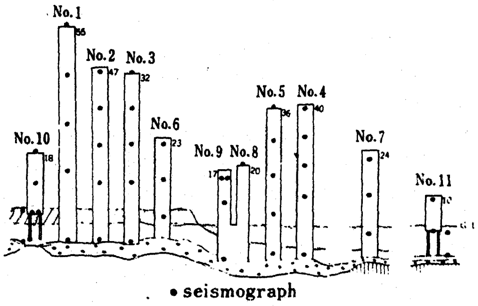


Fig. 4 Location of Seismograph

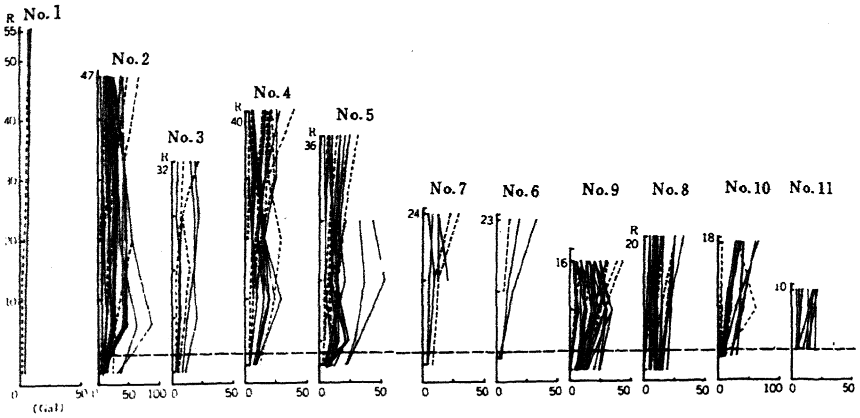
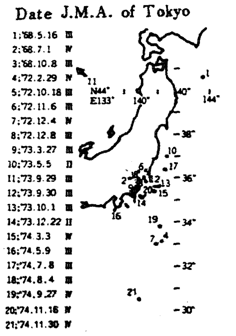


Fig. 6 Distribution of Maximum Acceleration of each Building during Earthquakes



Date	J.M.A. of Tokyo
1;'68.5.16	III
2;'68.7.1	IV
3;'68.10.8	III
4;'72.2.29	IV
5;'72.10.18	III
6;'72.11.6	III
7;'72.12.4	IV
8;'72.12.8	III
9;'73.3.27	III
10;'73.5.5	II
11;'73.9.29	III
12;'73.9.30	III
13;'73.10.1	III
14;'73.12.22	II
15;'74.3.3	IV
16;'74.5.9	III
17;'74.7.8	III
18;'74.8.4	III
19;'74.9.27	IV
20;'74.11.16	IV
21;'74.11.30	IV

Fig. 5 Outline of Observed Earthquakes

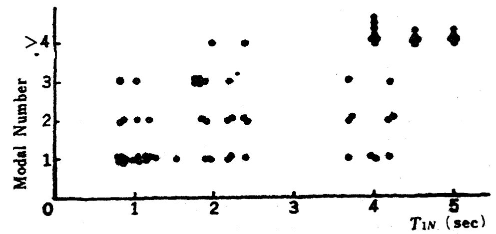


Fig. 8 Main Periods Observed Maximum Acceleration during Earthquakes

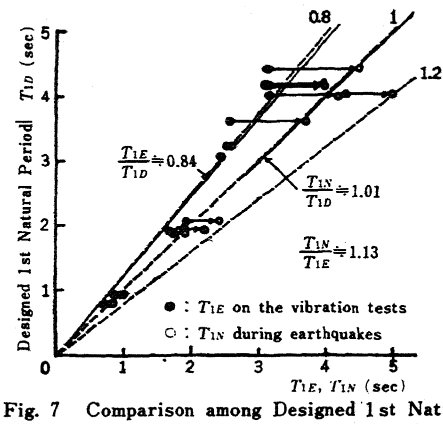


Fig. 7 Comparison among Designed 1st Natural Period, Measured One on Vibration Tests and Observed One during Earthquakes

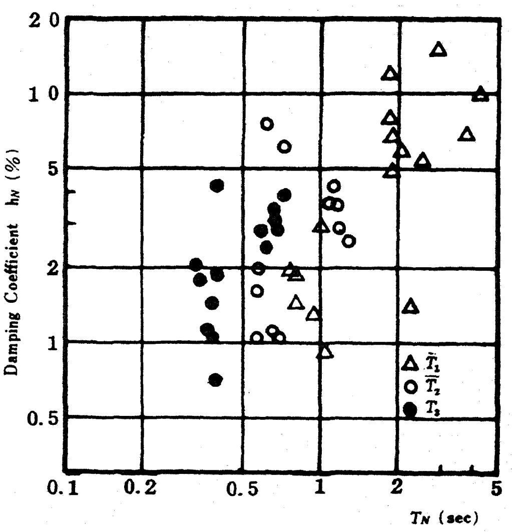


Fig. 9 Relationship between Natural Period and Damping Coefficient during Earthquakes

Table. 1 General Discription of Buildings and Results of Vibration Tests and Results Obtained from Earthquake Observations

Building No.	Stories above and under ground	Building eaves height, in meter	Typical floor dimensions, in meter	Structural material	Foundation	(upper column) Transverse, (middle column) Longitudinal, (lower column) Torsion												
						Designed natural periods (sec)			Results of vibration tests						Test method	Results obtained from Earthquake observations		
									natural periods (sec)			damping coefficients (%)				natural periods (sec)		
						1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd		1st	2nd	3rd
1	55 3	210.2	45.9 ×59.8	Steel	mat	5.08 5.18	1.54 1.69	0.80 0.93	4.40 3.96 2.81	1.29 1.27 0.98	0.66 0.70 0.57	0.8 0.9 0.7	1.0 0.9 1.1	1.1 1.1	A+B		1.4 1.3	0.8 0.7
2	47 3	169.8	25.9 ×79.8	Steel	mat	4.04 4.42	1.25 1.53	0.64 0.88	4.30 3.10 3.30	1.28 1.10 1.10	0.65 0.65 0.60	0.5 1.8 1.1	0.7 3.4 3.9	2.5 2.9 1.6	A+B	5.0 4.5	1.5 1.3	
3	32 3	151.2	54.0 × 54.0	Steel	mat	4.39 4.31	1.55 1.53	0.82 0.81	3.08 3.00 2.33	1.05 1.03 0.93	0.58 0.56	0.7 0.6 0.7	1.0 1.5 1.4	1.4 1.5	A+B		1.2 1.10	0.61 0.63
4	40 3	150	51.4 × 48.4	Steel	mat	3.77 3.77	1.21 1.22	0.65 0.66	3.17 3.14 2.47	1.01 1.02	0.54 0.55	0.9 0.7 0.8	1.3 1.3	1.5 1.4	A+B	4.0 4.0	1.3 1.2	0.7 0.7
5	36 3	147.0	42.5 × 76.8	Steel	mat	4.24 3.93	1.33 1.34	0.70 0.79	3.14 2.56 3.24	0.95 0.89 1.1	0.47 0.48	1.02 1.31			A+B	4.2 3.7	1.2 1.2	0.68 0.72
6	23 1	91.8	28.8 × 68.8	Steel	mat	2.22 1.97	0.71 0.68	0.38 0.39	2.0 1.6	0.58 0.51					C			
7	24 2	88.8	25.2 × 54.0	Steel	mat	2.32 2.23	0.72 0.73	0.38 0.40	2.1 2.0	0.64 0.64					C	2.2 2.0		
8	20 3	68.8	22.5 × 37.5	Steel	mat	2.08 1.95	0.71 0.68	0.47 0.39	1.91 1.89 1.54	0.62 0.64		2.1 1.9 3.1	1.8 1.9		A	2.4 2.2	0.68 0.71	0.40 0.39
9	17 3	57.7	22.5 × 30.0	Steel	mat	1.93 1.88	0.68 0.67	0.41 0.40	1.66 1.71	0.55 0.57	0.32 0.32	1.5 1.5	1.7 1.4	2.4 1.7	A	1.8 1.9		
10	18 1	48.9	13.5 × 24.0	reinforced concrete	pile	0.95 0.81	0.32 0.28	0.19 0.16	0.83 0.68 0.60	0.27 0.24 0.23	0.15 0.13	1.5 3.1 2.4	3.1 2.9 2.0	6.5 6.5	A	1.0 0.82		
11	10 0	26.8	15.2 ×135.5	reinforced concrete	pier	0.61			0.36 0.28			9.6 10.3			A	0.37 0.33		

Explanatory notes

Test method
- A : forced vibration test using shaking machine
- B : free vibration test using pendulum
- C : observation of microtremors