COMPARATIVE FORCED VIBRATION TEST OF TWO BWR-TYPE REACTOR BUILDINGS

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SUMMARY

The highlight of this paper is the comparative forced vibration test of two GE-460 MWe BWR type reactor buildings by means of a vibrator. The tested nuclear power plants are the Fukushima nuclear power plant No. 1 of the Tokyo Electric Power Co. (hereinafter referred to as "Fukushima") and the Shimane nuclear power plant of the Chugoku Electric Power Co. ("Shimane"). They are almost the same in both structure and function, but are built on rock of quite different rigidity. The shear wave velocity of the Fukushima site is about 1/3 of that of the Shimane site.

Immediately after completion of each reactor building, the forced vibration test was performed for Fukushima in November of 1969, and for Shimane in August of 1972. In each case a vibrator with its maximum exciting force of 3 tons was installed on the refueling floor. The vibration responses of the structure and equipment were measured by a new measuring system which was named MIK utilizing the correlation technique.

On the other hand the computer simulation analyses were carried out by using the vibration models which consist of foundation, building, shielding wall, primary containment vessel, gamma-shielding wall and reactor pressure vessel. Then the masses, rigidities and internal viscous damping coefficients were correctly determined by continuing simulation analyses until the computed resonance and phase difference curves coincided fairly with the tested ones.

The main remarks derived from the tests and analyses are as follows:

(1) In first and second modes of each reactor building, the vibration characteristics were found to be quite different. Because the rock of Fukushima is softer than that of Shimane, the 1st and 2nd damping factors as well as their natural periods are respectively larger in case of Fukushima as follows:

Fukushima;	1st 0.25 sec., 34%	2nd 0.17 sec., 8%
Shimane;	1st 0.19 sec., 2%	2nd 0.13 sec., 5%

(2) In each third vibration mode, the vibration of the reactor pressure vessel was much pronounced at 0.09 sec. The damping factors were found to be almost the same value, around 3%, in both plants.

(3) Thus, the above-mentioned method assuming different internal viscous damping coefficients for each vibration element was demonstrated and should be useful for seismic analysis of any type of nuclear power plant placed on any condition of foundation.

1. Introduction

At the 1st SMiRT Conference, K. Muto and K. Omatsuzawa presented a paper (see Muto [1]) regarding the earthquake observation and its simulation analysis of the Fukushima Nuclear Power Plant Unit No. 1 of the Tokyo Electric Power Co., (hereinafter referred to as "Fukushima" shown in Fig. 1).

Introducing the Shimane Nuclear Power Plant of the Chugoku Electric Power Co., ("Shimane" shown in Fig. 2) in this paper, the comparative forced vibration test of both Fukushima and Shimane by means of a vibrator is described. Both plants are almost identical in both structure and function. The soil foundation of Fukushima consists mainly of sandy-mud stone, while that of Shimane is composed of tuff and stone. The Young's modulus of Shimane soil foundation is about 12 times that of Fukushima.

The test results of both plants indicate that the difference of supporting soil foundation has a great deal of influence on both the vibration modes and the damping factors of the plants. Since the authors consider these vibration characteristics very important from the viewpoint of aseismic design and site selection of nuclear power plants, this paper is focussed on the differences of the supporting soil foundations between the two plants.

2. Outline of the Reactor Buildings

Each nuclear power plant has a boiling water type reactor (460 MWe, GE type). The outline and dimension of the structure are shown in Fig. 3. The building is composed of reinforced concrete structure from the basement (BMT) to the fifth floor (refueling floor) with a steel roof truss (ST). At the center of the building is a reactor pressure vessel (RPV) which is surrounded by a concrete gamma shield wall (GSW), a bulb shaped steel primary containment vessel (PCV) and a reinforced concrete shield wall (SW), in order.

Each plant is designed by both static and dynamic aseismic design procedures to ensure the highest safety design. Namely, the static design is performed on the basis of seismic coefficient 0.48 which is derived from multiplying the seismic coefficient 0.20 (specified by the Japanese Building Code) by the importance factor 3 and the regional coefficient 0.8.

On the other hand, the dynamic design is conducted on the basis of the earthquake response analysis. In the analysis, applied are the modal damping factor of 5% and such input earthquake waves as El Centro 1940 (NS) and etc. with their maximum intensity of acceleration of 180 gal in case of Fukushima and of 200 gal in case of Shimane.

3. Soil Condition

The soil foundation of Fukushima consists mainly of sandy-mud stone, while that of Shimane is composed of tuff and stone. The primary wave velocity Vp, the secondary wave velocity Vs and Young's modulus Es of both soil foundations are introduced by Prof. S. Okamoto as shown in Table 1 (see Okamoto [2]). It should be noted that Es of Shimane is found to be 12 times that of Fukushima.

Table 1 Soil Constants

	Fukushima	Shimane
Vp (km/sec.)	1.7	3.7
Vs (km/sec.)	0.61	1.8
Es (t/cm^2)	18	220

4. Vibration Test

4.1 Testing Method

The forced vibration tests by a vibrator were conducted at Fukushima in November, 1969 and Shimane in August, 1972 with respect to two directions of each reactor building as illustrated in Fig. 3.

The vibrator (with the frequency range from 0.2 Hz to 20 Hz and the maximum exciting force of 3 tons) was installed on the fifth floor. The horizontal displacements at BMT, 2F, 5F, RF, RPV, GSW and PCV, the rotational movement at BMT, and the phase lags at respective points were measured by the MIK system (see Muto [3]).

In this paper the comparative study is described with respect to the A direction in Fig. 3. The test results are presented as vibration modes and resonance curves. The horizontal axis of the resonance curves is expressed by the frequency (f) of the vibrator, while the vertical axis is presented by dividing the amplitude A by f^2 (namely, A/f^2) where A is converted in terms of unbalanced moment of 20 kg.m.

4.2 Test Results

(1) Resonance curves

Fig. 5 shows the resonance curves at RF, 5F and the top of RPV. The resonance periods from the 1st to 3rd order are read as shown in Table 2 by referring to the resonance curves and to the hereinafter-mentioned analytical results.

Table 2 Resonance Periods

	Fukushima	Shimane
1st	0.25 sec.	0.19 sec.
2nd	0.17	0.13
3rd	0.089	0.086

Table 2 indicates that the 1st and 2nd periods of Fukushima are larger by 30% than those of Shimane. This phenomenon is considered to be influenced by the softness of the supporting soil foundation. But, the 3rd periods are almost similar in both plants because the 3rd modes show the vibration of RPV itself as shown in Fig. 6.

(2) Resonance vibration modes

Fig. 6 shows the resonance vibration modes at the above-mentioned resonance periods. The black marks in Fig. 6 indicate the tested amplitudes, neglecting phase lags. The 1st and 2nd modes are normalized by the amplitude at 5F, while the 3rd mode is normalized by it at the top of RPV. The resonance modes obtained by the hereinafter-mentioned simulation analysis are illustrated by the solid lines in Fig. 6.

In the 1st and 2nd modes the vibration of the building is much pronounced. On the other hand the 3rd mode corresponds to the first mode of RPV.

(3) Movements of base mats

The horizontal and rotational movements of the base mat are enlarged in Fig. 7 in order to show them clearly. The results of the simulation analysis are shown by the solid and dotted lines in Fig. 7. It is found that the base mat does not remain in a plane but deforms as shown in the sketch.

The total displacement at 5F can be decomposed into an elastic deformation of the reactor building and the displacement caused by the movement of the base mat. In Fig. 7, the total displacement δtotal is expressed by the solid line, while the displacements by the horizontal and rotational movement, δh and $\delta\theta$ respectively, are presented by the dotted lines. The percentage of $\delta h + \delta\theta$ against δtotal (namely, $\delta h + \delta\theta / \delta$total) of Fukushima is 60%, while the one of Shimane is 25%, in the 1st mode.

This means that since the soil movement of Fukushima is very large, the vibration characteristics, particularly the damping factors, are greatly affected by the soils.

5. Simulation Analysis

5.1 Vibration Model

The simulation analysis was performed by the same model and the equation of motion mentioned in reference [1]. The model is shown in Fig. 4 and the equation is cited below.

$$[M]\{\ddot{V}\} + [C]\{\dot{V}\} + [K]\{V\} = \{F\} \qquad (1)$$

where,

$$\{F\} = 0.0020 \cdot (2\pi f)^2 \cdot \sin 2\pi f t \qquad (2)$$

an exciting force (ton) at 5F obtained due to the vibrator

5.2 Input Phtsical Constants

The Young's moduli and the internal viscous damping coefficients utilized in the analysis are shown in Table 3.

Table 3 Physical Constants

		Fukushima	Shimane
Young's modulus (t/cm^2)	soil	45	550
	concrete	520	
	steel	2100	
	RPV, PCV	2100	
Damping coefficient (sec.)	soil	0.0414	0.012
	concrete	0.00064	
	steel	0.00032	
	RPV, PCV	0.0016	

The physical constants of reinforced concrete and steel are the same as used in reference [1]. But the internal viscous damping coefficients of RPV and PCV are revised from 0.00032 sec. to 0.0016 sec. for further improvement of simulation analysis.

Regarding the soil data, the Young's moduli of Fukushima and Shimane are shown to be 18 t/cm^2 and 220 t/cm^2 respectively in Table 1 based on reference [2]. However, the authors found it necessary for the simulation analysis to revise the constants into the values shown in Table 3. Namely the Young's modulus of Fukushima is quoted to be 45 t/cm^2 from reference [1], while that of Shimane is adjusted to be $45 \times \frac{220}{18} = 550\ t/cm^2$ by referring to the Young's modulus ratio between both plants. On the other hand, the internal viscous damping coefficient of Fukushima is also quoted to be 0.0414 sec. from reference [1], while that of Shimane is calculated to be 0.012 sec. on the basis of the energy dissipation theory where the damping coefficient is inversely proportionate to the square root of Young's modulus.

5.3 Comparison between Analyzed and Tested Results

Substituting the physical constants into eq. (1), the resonance curves can be computed with respect to each frequency f of the vibrator. Here the analyzed resonance curves at 5F of both plants are shown with the tested ones in Fig. 8. From this figure a fairly close agreement can be seen between both resonance curves.

Regarding the resonance vibration modes, refer to 4.2.

5.4 Damped Natural Periods and Modal Damping Factors

The damped natural periods Ti and their modal damping factors hi from the 1st to 3rd order are shown in Table 4. These values are obtained by the solution method of damped free vibration described in reference [1].

Table 4 Damped Natural Periods and Modal Damping Factors

		Fukushima	Shimane
1st	T_1	0.25 sec.	0.19 sec.
	h_1	33.7 %	2.1 %
2nd	T_2	0.18 sec.	0.13 sec.
	h_2	8.4 %	4.9 %
3rd	T_3	0.089 sec.	0.089 sec.
	h_3	5.4 %	5.2 %

From Table 4 it should be noted that in the case of Fukushima the 1st damping factor 33.7% is larger than the 2nd one 8.4%, while in the case of Shimane the 1st damping factor 2.1% is smaller than the 2nd one 4.9%.

This opposite phenomenon is influenced by the interaction of steel roof truss.

6. Summary

The main remarks derived from the test and analysis are as follows:

(1) Since the supporting soil foundation of Fukushima is softer than that of Shimane, both the resonance periods and the damping factors are larger.

(2) Concerning RPV, there is little difference between the vibration characteristics of both plants.

(3) The rigidity of soil supporting foundations is found to have a great deal of influence on the resonance periods and damping factors of reactor buildings. Therefore, site selection of nuclear power plants must be reviewed as a matter of utmost importance from this point of view.

[REFERENCES]

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[2] Okamoto, S.: "Aseismic Design" (Japanese), Journal of the Japan Society of Civil Engineers, Vol. 57-2, P28 ~ 34, February, 1972

[3] Muto, K. et al.: "New Measuring Method of Vibration Using Correlation Technique", a paper at Fifth World Conference on Earthquake Engineering, Rome, 25-29, June, 1973

Fig. 1 the Fukushima Nuclear Power Plant NO. 1

Fig. 2 the Shimane Nuclear Power Plant

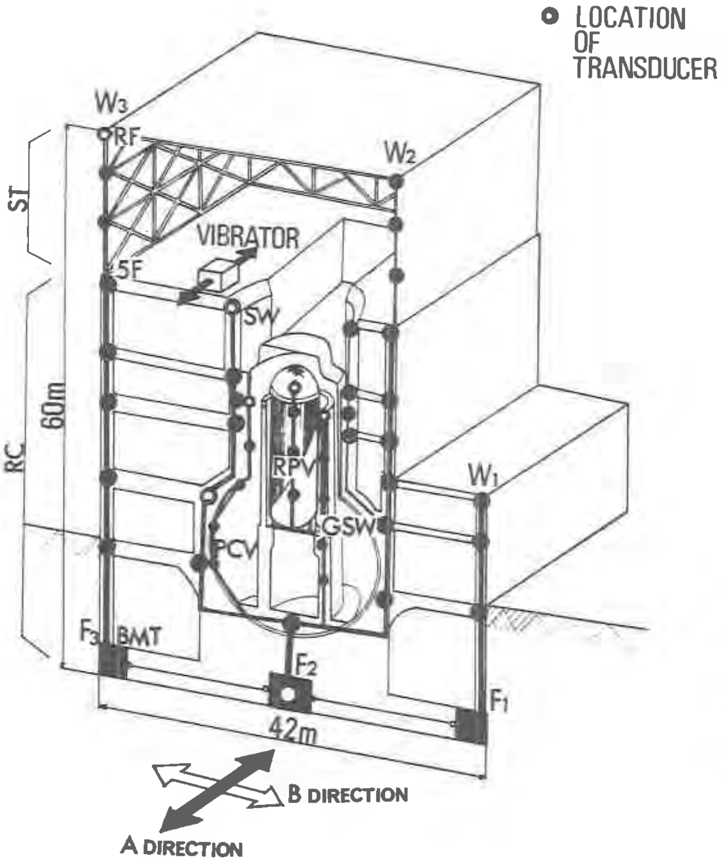


Fig. 3 Concentrated Masses and Location of Transducer

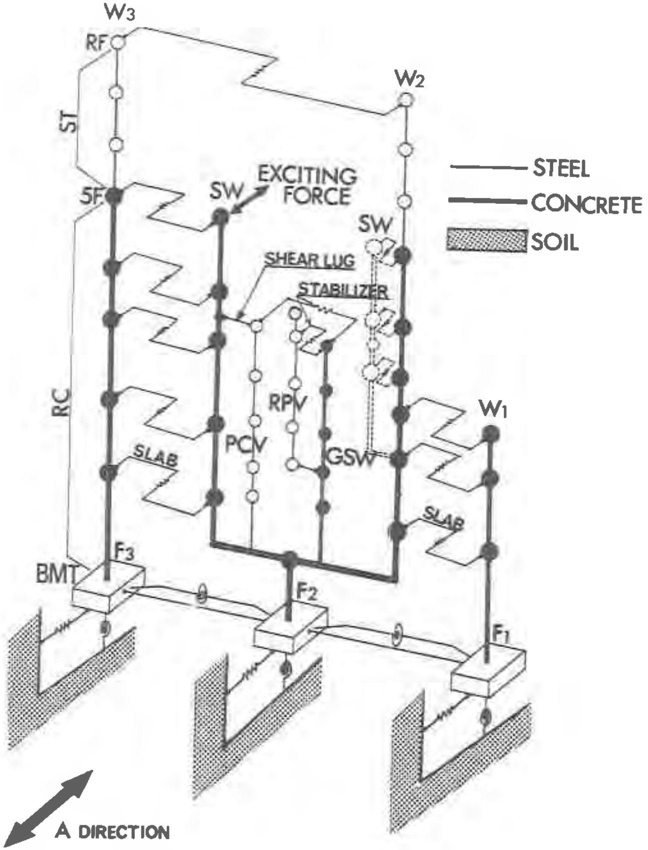


Fig. 4 Mathematical Vibration Model in A Direction

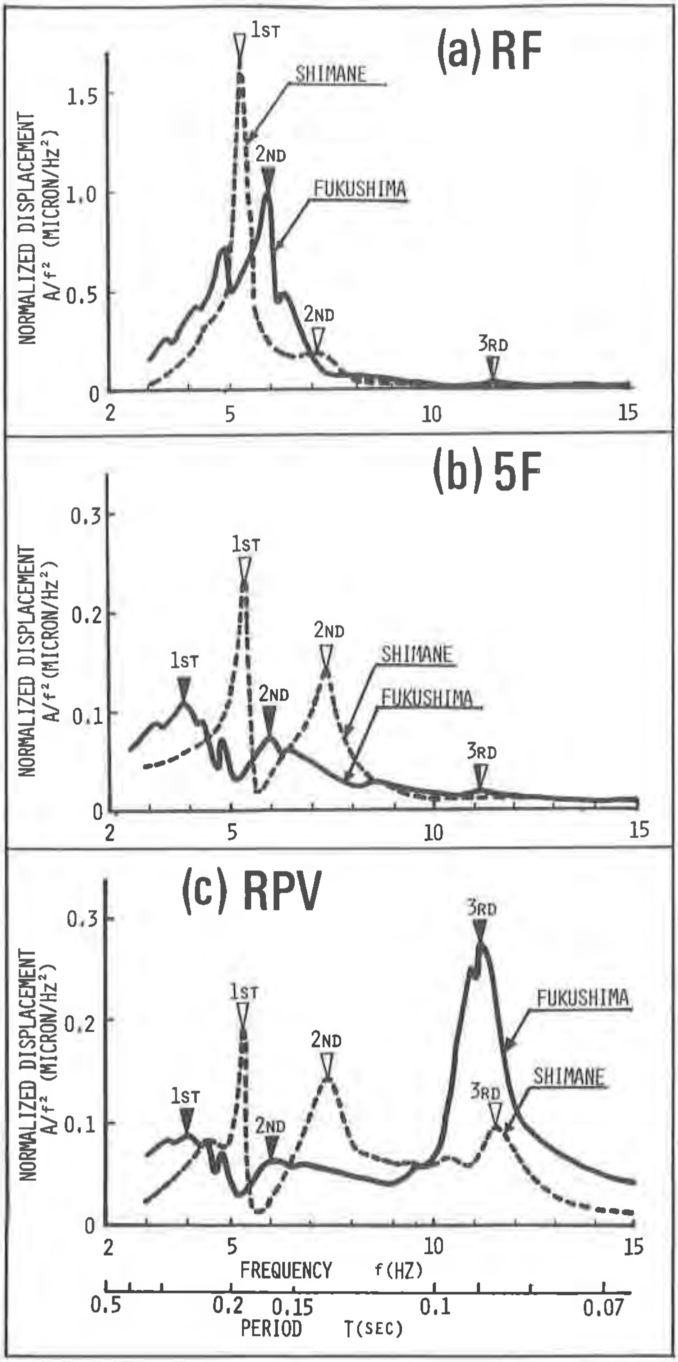
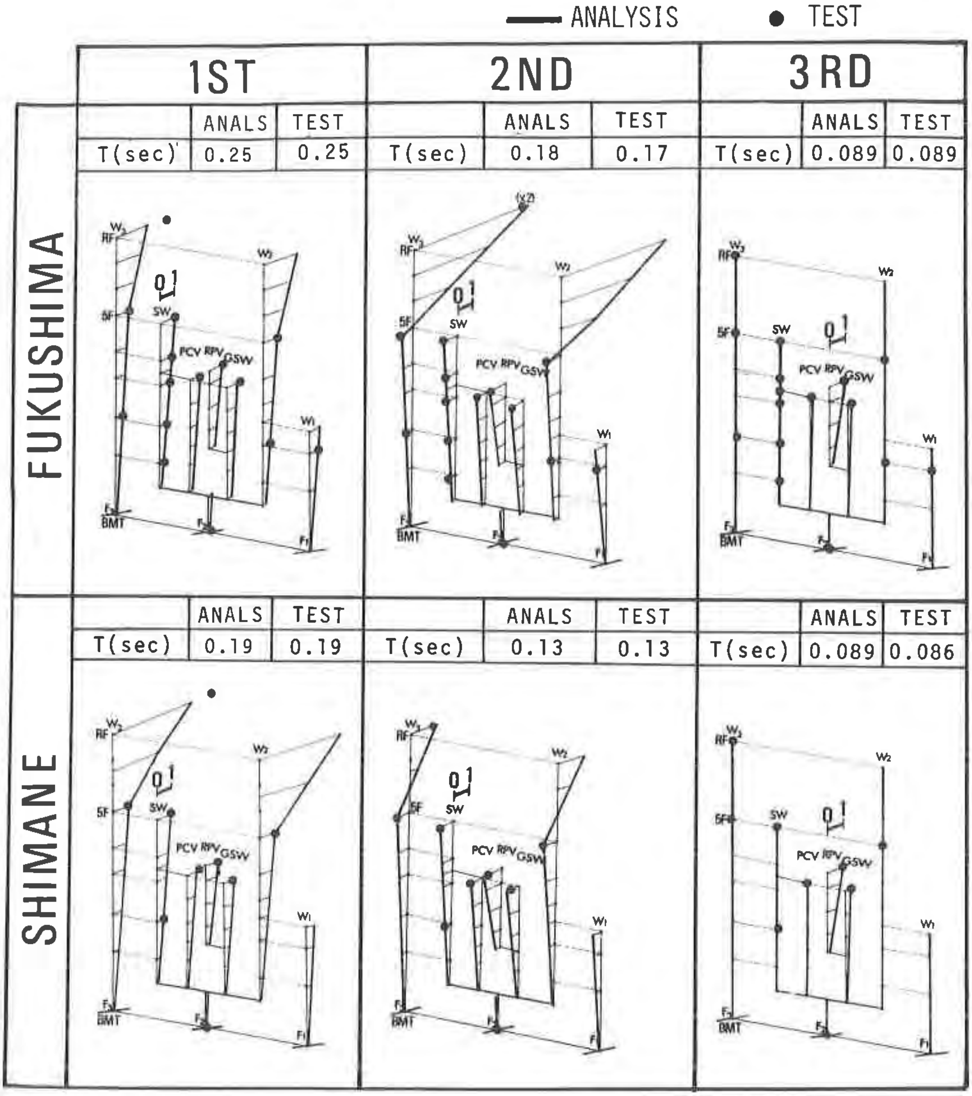


Fig. 5 Tested Resonance Curves



	1ST ANALS T(sec)	1ST TEST T(sec)	2ND ANALS T(sec)	2ND TEST T(sec)	3RD ANALS T(sec)	3RD TEST T(sec)
FUKUSHIMA	0.25	0.25	0.18	0.17	0.089	0.089
SHIMANE	0.19	0.19	0.13	0.13	0.089	0.086

Fig. 6 Comparison Between Analyzed and Tested Resonance Vibration Mode Shapes

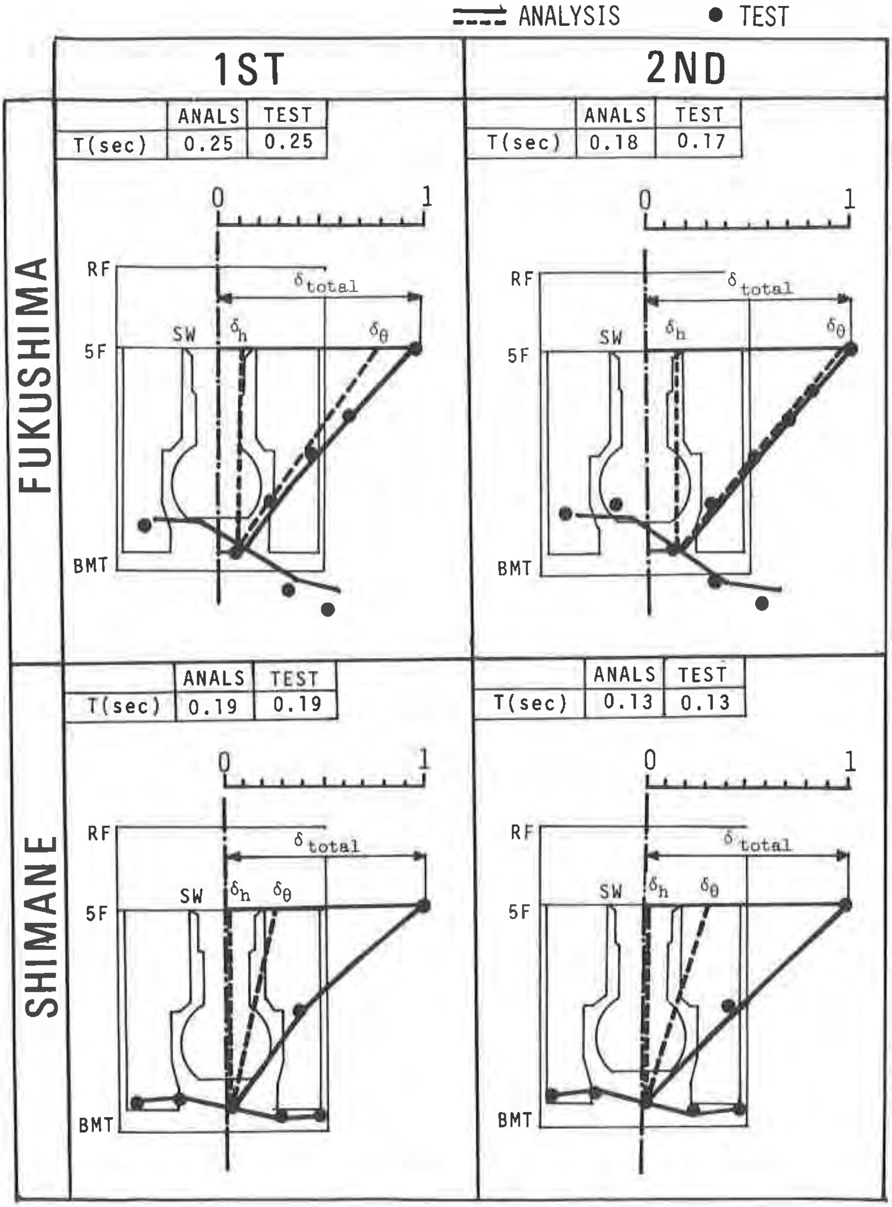
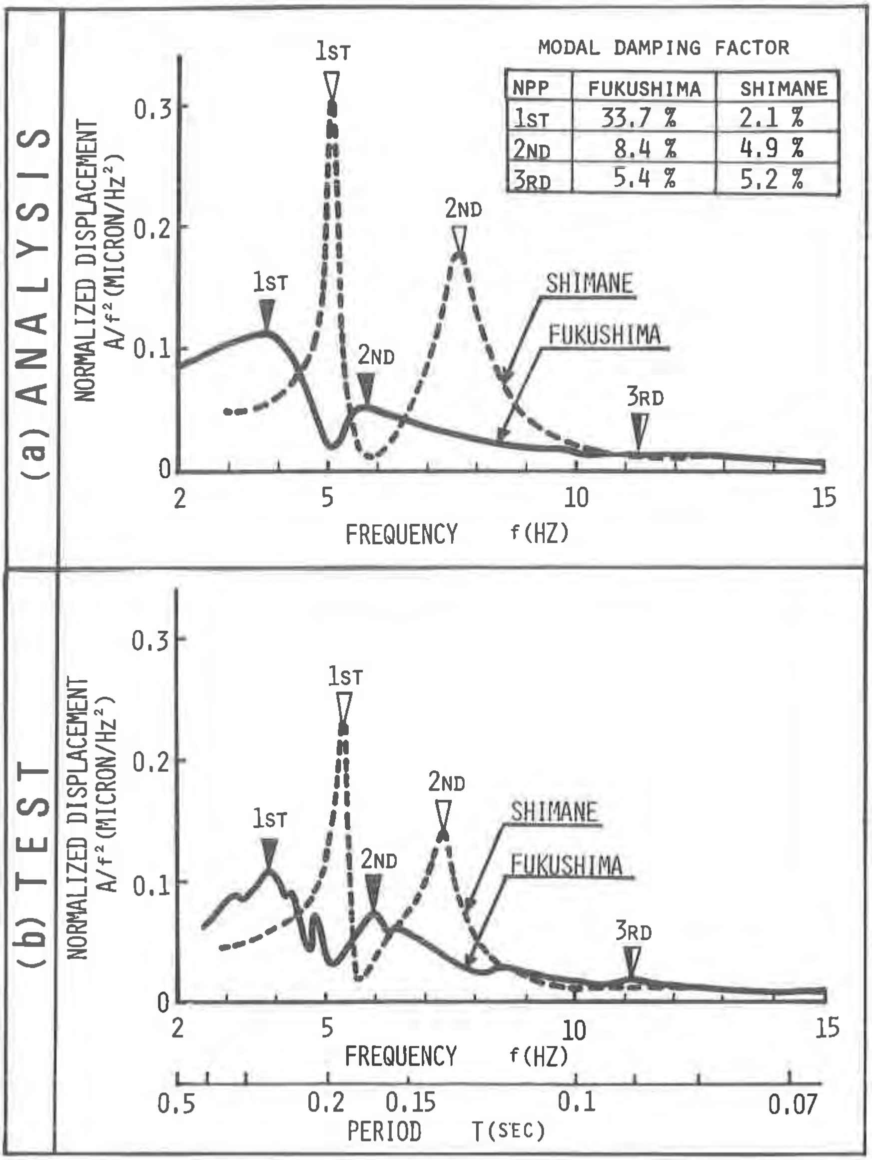


Fig. 7 Comparison between Analyzed and Tested Movements at BMT



MODAL DAMPING FACTOR

NPP	FUKUSHIMA	SHIMANE
1ST	33.7 %	2.1 %
2ND	8.4 %	4.9 %
3RD	5.4 %	5.2 %

Fig. 8 Comparison between Analyzed and Tested Resonance Curves at 5F