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# VIBRATION TEST OF A MODEL OF NUCLEAR POWER PLANT USING A LARGE SHAKING TABLE (PART 1 PWR INTERACTION MODEL)

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## SUMMARY

The object of this research is to investigate the elasto-plastic behavior of a reactor building with its related mechanical equipment subjected to a severe earthquake excitation through a shaking table test. Test specimen is simplified and scaled of the standard PWR type reactor building incorporated with the mechanical equipment.

The test model was subjected to a dynamic excitation up to 3 time of extreme design level. Finally the entire web wall of the structure shear cracked.

The vibration test were well simulated, using the flexural shear system in a way similar to the practical design method.

## INTRODUCTION

This paper investigates the elasto-plastic behavior of a PWR type reactor building through a dynamic test using the large scale shaking table at Nuclear Power Engineering Test Center in Japan (NUPEC).

Main object of this research work are to prove the soundness of the reactor building exposed to the design level earthquake, to prove the availability of the conventional analytical method, and to examine the structure-equipment interaction effect.

It should also be mentioned that this research report summarizes the corroborative research work of 10 Japanese Electric Power Companies on the theme "Vibration Test of Model of Nuclear Power Plant Using A Large Vibration Table".

## TEST PROGRAM

Test Specimen A simplified scaled model was used for the test specimen in consideration of the limitation in the capacity of the vibration table and the difficulty of constructing the test specimen, under the premises that the dynamic characteristics and structure-equipment interaction effect of the actual PWR type reactor building could be simulated.

Of the PWR type reactor building, the Inner Concrete which is a structure supporting the reactor coolant system was selected as the object of the test. A realistic 3 story structure with 3 stage support of equipment, scaled down 1/2 from the actual size was used for the test specimen. The dynamic characteristics and the restoring force characteristics were set to satisfy the law of similarity requirements.

The shape of the test specimen is shown in Fig.-1. The floor plan of the structure was a II shape 3 storied reinforced concrete model. The mechanical equipment consist of 3 stage supported steel cylinder. The type of support system were the snubber type for the upper stage and the tie rod type for the middle and lower stage.

Material mechanical property from the material test implemented just before the vibration test is shown in Table-1.

Vibration Program Input earthquake wave was one acceleration waveform and the vibration amplitude was increased by step up to the ultimate stage. The response wave on the foundation of a standard PWR type reactor building standing on a standard rock by an artificial earthquake (M8.5, $\Delta$=68km, Phase angle HACHINOHE) was used for this waveform. Input acceleration waveform and response spectra are shown in Fig.-2. Input earthquake amplitude was increased up to three times of extreme design level Ao.

Since the test specimen consist of the structure incorporated with mechanical equipment, to obtain the dynamic characteristics of the structure itself, 4 levels of vibrations within the elastic range was applied to the structure alone. Thereafter, mechanical equipment was installed and in this incorporated condition, 9 levels of vibration ranging from the elastic state to the ultimate state were applied.

## TEST RESULTS

Vibration test results on PWR type structure model and structure-equipment interaction model are summarized as follows.

Outline of Test Results Maximum response quantities of typical vibration stage are shown in Table-2 and the crack pattern of the structure wall after the final level test is shown in Fig.-3.

The structure roughly retained an elastic state up to 380gal(0.7Ao) vibration applied to the structure alone and up to 695gal(1.0Ao) vibration applied to the structure-equipment interaction model. The shear stress of the web wall reached 35 - 40 $kg/cm^2$ (0.14 - 0.16Fc) at 1712gal(3.0Ao) and shear crack developed on the entire wall surface of each story as shown in Fig.-3, but ultimate failure state was not reached. The strain of the longitudinal reinforcing bar at the bottom of the flange wall stay below the yield point.

Dynamic Characteristics In order to evaluate the effective horizontal input, the rotational component of the vibration table was removed from the observed horizontal response acceleration records.

The natural frequency and damping ratio was obtained by the band width method. The deterioration of the natural frequency and damping ratio in accordance with input level are shown in Fig.-4.

The natural frequencies of the structure model and the structure-equipment interaction model were 18.4Hz and 14.1Hz respectively. Above 1012gal(1.5Ao) vibration of the interaction model, frequency became lower and finally at 1712gal(3.0Ao) vibration, frequency dropped to 8.5Hz.

The damping ratio at the natural frequency of the structure model was approximately 1%, and that of the structure-equipment interaction model was 3-7%.

Shear Force-Story Displacement Relation The envelope skeleton curve of the shear force-story displacement is shown in Fig.-5. The approximated bilinear skeleton curve was obtained by the least squares method. The shear stress at the break point of the approximated curve was 18.9 - 23.2 $kg/cm^2$ and the stiffness ratio of the second branch was 0.18 - 0.34. The shear stress at the break point approximately corresponded to the shear cracking stress of the web wall and was between the two previously proposed equations $\sqrt{\sqrt{Fc}(\sqrt{Fc}+\sigma_o)}$(Ref.-2) and 0.1Fc.

## SIMULATION ANALYSIS

Simulation analysis was conducted to clarify the availability of the analytical method commonly used in the practical design, and to examine the structure-equipment interaction effect.

Analysis Model In making the simulation analysis, the structure and the mechanical equipment were modelled to the flexural shear system with lumped mass and the equipment support structures were modelled to the scalar spring (Fig.-6).

The spring constant and damping ratio of the support structures were set based on the vibration test results, because of the inelastic behaviors.

The hysteretic restoring force characteristics were represented by the combination of the trilinear skeleton curve (Table-4) and the peak oriented hysteresis loop curve.

The input motion to the analysis model were considered both horizontal motion and the rotational motion measured at the base of the specimen simultaneously. The input levels were set at 5 levels from 418gal(0.7Ao) to 1712gal(3.0Ao).

Analysis Results The dynamic characteristics of the structure, as seen from the Fourier spectrum of the structure model under the low level earthquake vibration test (Fig.-7), show that the analysis results favorably simulate the test results. Also the dynamic characteristic of the equipment, as seen from the Fourier spectrum of the interaction model(Fig.-8) and the maximum response of the equipment(Fig.-9), the analysis results respectively coincide with test results. It has been confirmed that the analytical model and method possess sufficient validity.

As for the restoring force characteristics of the structure, the shear force-story displacement relationship at above 1012gal(1.5Ao) overestimates the stiffness deterioration property at the first story as shown in Fig.-10, but it has been confirmed that overall response results approximately correspond to the test results.

The structure-equipment interaction effect was apparently observed by comparing the floor response spectrum of equipment independent model with that of structure-equipment interaction model (Fig.-11). The peak of the response spectrum of the structure-equipment interaction model cannot be observed. Therefore, the response quantities of the equipment calculated from the floor response spectra became extremely smaller than conventional independent model as shown in Table-5. The response of the equipment could be reasonably simulated by using structure-equipment interaction model.

## CONCLUSION

This paper presented the experimental results as well as the analytical simulations of the vibration tests on a PWR type structure-equipment interaction model and is summarized as follows.

(1) The test model was subjected to earthquake excitation on the vibration table up to 1712gal(3.0Ao) input amplitude. As the input amplitude increased, cracking gradually progressed, and finally the entire web wall shear cracked.

(2) The vibration tests were well simulated with an analytical method which is conventionally used in a practical design of the reactor building. It has been confirmed that the analytical model and method possess sufficient validity.
(3) The response quantities of the mechanical equipment derived from the equipment independent model in a way similar to the practical design method were larger than those of experimental results. It has been confirmed that the structure-equipment interaction model is reasonable.

## ACKNOWLEDGEMENT

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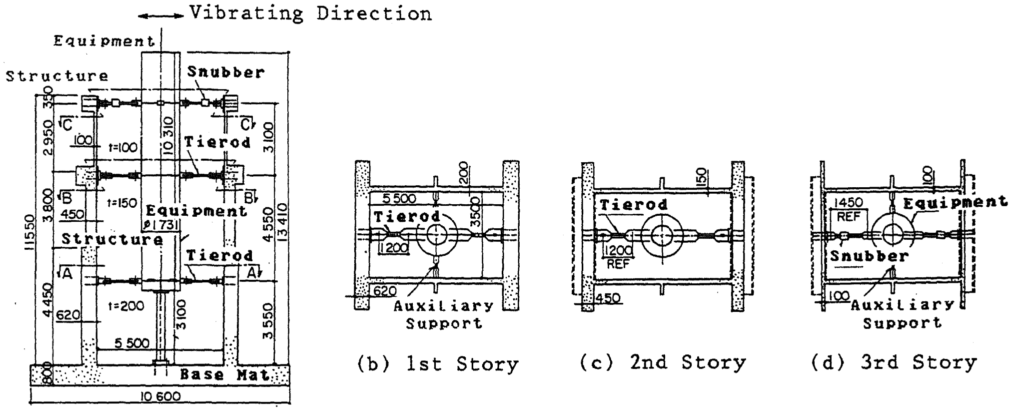


(a) Section (b) 1st Story (c) 2nd Story (d) 3rd Story

Fig.-1 PWR Interaction Test Model (unit:mm)

Table-1 Material Mechanical Properties

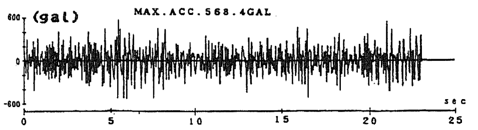
(a) Concrete

| Position | | Strength (kg/cm²) | | Young's Modulus ($10^5$kg/cm²) | | Poisson's Ratio ($F_c$/3) |
|---|---|---|---|---|---|---|
| | | Compressive | Tensile | Dynamic | Static($F_c$/3) | |
| 1st Story | Upper | 218 | 19.3 | 2.77 | 2.36 | 0.18 |
| | Lower | 251 | 24.0 | 2.88 | 2.36 | 0.19 |
| 2nd Story | | 296 | 26.9 | 3.05 | 2.56 | 0.19 |
| 3rd Story | | 258 | 21.9 | 2.38 | 2.28 | 0.19 |

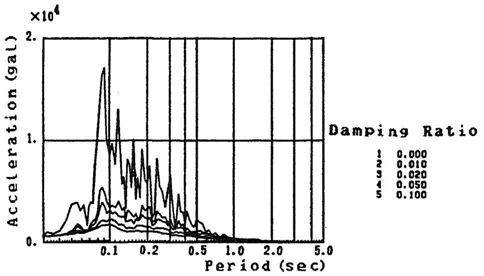
(b) Reinforcing Bar

| Diameter (mm) | Yield Point | Tensile Strength | Young's Modulus |
|---|---|---|---|
| D19 | 4200 | 6240 | $1.97\times10^6$ |
| D16 | 4370 | 6340 | $1.97\times10^6$ |
| D13 | 4620 | 6550 | $2.03\times10^6$ |

(unit: kg/cm²)

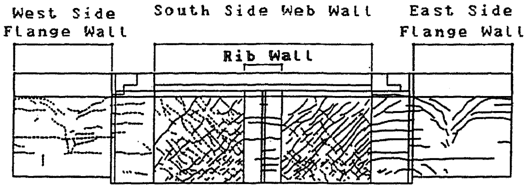


(a) Acceleration Wave

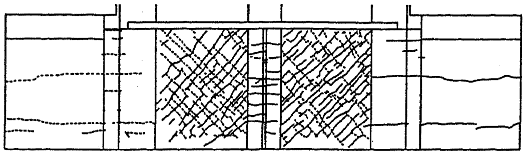


(b) Response Spectrum

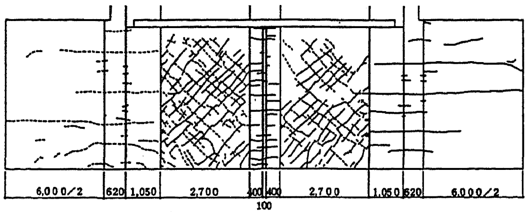
Fig.-2 Input Earthquake Motion



(c) 3rd Story Wall



(b) 2nd Story Wall

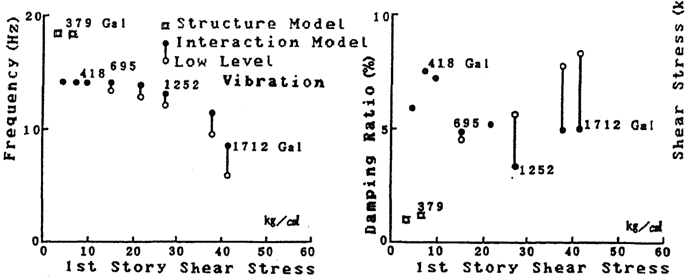


(a) 1st Story Wall

Fig.-3 Final Crack Pattern of Structural Wall

Table-2 Maximum Responses

| Reponses | | Structure | Structure-Equipment Interaction | | | |
|---|---|---|---|---|---|---|
| | | 380 gal | 380 gal | 570 gal | 1140 gal | 1710-2 gal |
| Acceleration<br>(gal) | Base(Horizontal)<br>(Vertical)<br>Top of Structure<br>Top of Equipment | 379<br>68<br>946<br>— | 418<br>93<br>1350<br>2760 | 695<br>143<br>2020<br>4380 | 1252<br>420<br>3730<br>6700 | 1712<br>2060<br>7030<br>10500 |
| Shear Force | 1st Story (t)<br>$_{ave}\tau_1$ (kg/cm$^2$) | 160<br>6.6 | 237<br>9.7 | 372<br>15.2 | 667<br>27.2 | 1010<br>41.4 |
| Story Displacement | 1st Story (mm)<br>Angle (x10$^{-3}$rad) | 0.41<br>0.12 | 0.49<br>0.14 | 0.86<br>0.24 | 1.96<br>0.55 | 5.31<br>1.50 |
| Strain ($\mu$s) | Longitudinal Bar | 110 | 150 | 260 | 820 | 1860 |
| Upper Support | Snubber Force(t)<br>Displacement(mm) | —<br>— | 12.5<br>1.0 | 19.9<br>1.1 | 26.9<br>1.7 | 43.0<br>4.1 |



(a) Natural Frequencies (b) Damping Ratios

Fig.-4 Deterioration of Dynamic Characteristics

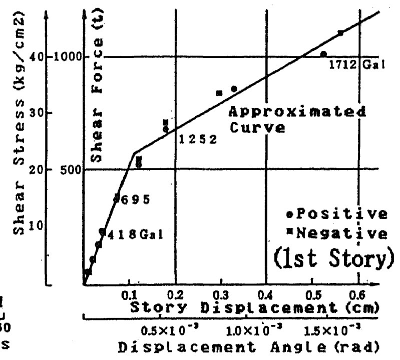


Fig.-5 Shear Force - Story Displacement Relation

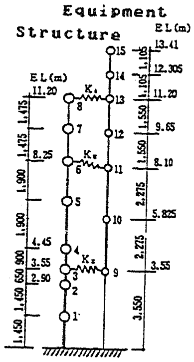


Fig.-6 Analysis Model

Table-3 Analysis Model of Restoring Force Skeleton Curves

| Component | | Strength | Strain |
|---|---|---|---|
| Shear Component | 1st Break | $\tau_1=\sqrt{\sqrt{F_c}\,(\sqrt{F_c}+\sigma_0)}$ | $\gamma_1=\tau_1/G$ |
| | 2nd Break | $\tau_2=1.35\tau_1$ | $\gamma_2=3\gamma_1$ |
| | Ultimate | Presented by YOSHIZAKI[2)] | $\gamma_3=4\times10^{-3}$ |
| Bending Component | 1st Break | $M_1=Z_e(f_t+\sigma_v)$ | $\phi_1=M_1/EI_e$ |
| | 2nd Break | Yield Moment by Tensile Bar | $\phi_2={}_r\varepsilon_y/X_{ny}$ |
| | Ultimate | Full Plastic Moment | $\phi_3=0.004/X_{nu}$ |

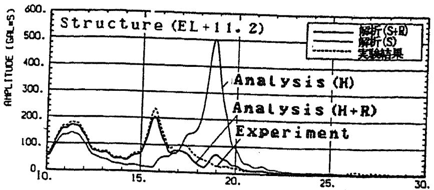


Fig.-7 Fourier Spectrum of Structure Model

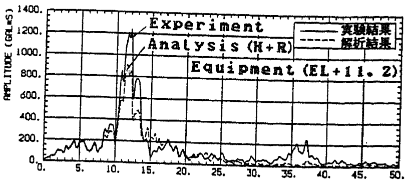
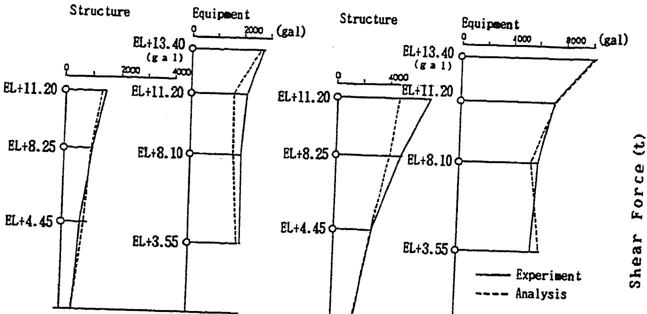
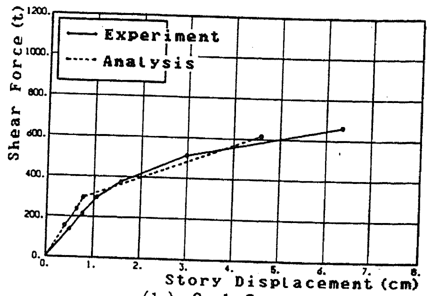


Fig.-8 Fourier Spectrum of Interaction Model



(a) 418gal(0.7Ao) (b) 1712gal(3.0Ao)

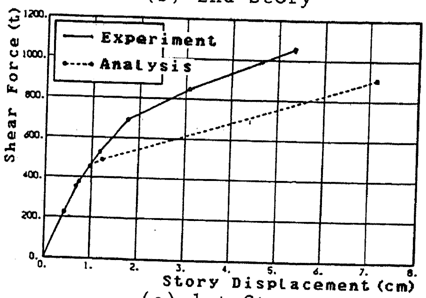
Fig.-9 Maximum Acceleration Responses



(b) 2nd Story

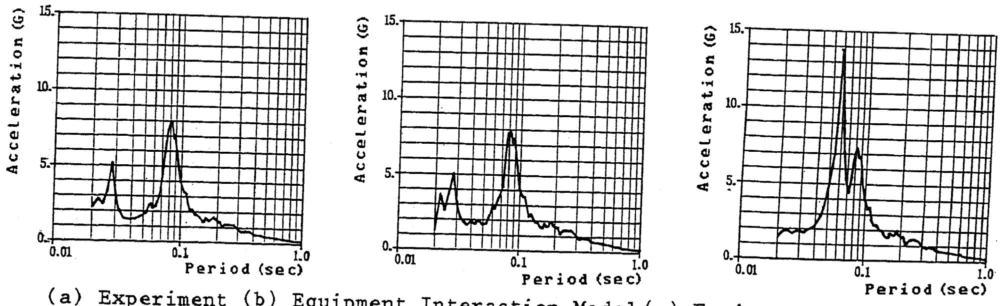
Table-4 Maximum Responses of Equipment

| Responses | | Experiment | Analysis | | |
|---|---|---|---|---|---|
| | | | Time Hystory Response of Interaction | Spectrum Modal Analysis | |
| | | | | Interaction | Independent |
| Acceleration (gal) | Top | 2758 | 2668 | 3759 | 11986 |
| | Upper | 2176 | 1591 | 1945 | 7557 |
| | Middle | 1951 | 1653 | 1251 | 1695 |
| | Lower | 2010 | 1879 | 1891 | 1709 |
| Reaction Force of Supports (t) | Upper | 22.4 | 19.2 | 17.8 | 69.4 |
| | Middle | 50.3 | 63.2 | 36.0 | 99.2 |
| | Lower | 24.5 | 15.9 | 22.8 | 43.4 |



(a) 1st Story

Fig.-10 Shear Force - Story Displacement Relation



(a) Experiment (b) Equipment Interaction Model (c) Equipment Independent Model

Fig.-11 Floor Response Spectra (418gal)