Seismic Proving Test of a Reinforced Concrete Containment Vessel (RCCV)
Part 3. Simulation Analysis of Shaking Table Tests

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ABSTRACT

Seismic proving tests carried out by the Nuclear Power Engineering Corporation (NUPEC) for
an 1/8 scale reinforced concrete containment vessel (RCCV) model using the large-scale, high-
performance shaking table of Tadotsu Engineering Laboratory are compared to simulation. This
paper describes the simulation analyses for the maximum design earthquake level (S1) and
extreme design earthquake level (S2) tests to evaluate the method which is used in the practical
seismic design of commercial nuclear power plants. The analysis results are compared to the
test results and the validity of the analysis method is discussed.

1. INTRODUCTION

Since 1980, NUPEC has conducted a series of seismic proving tests of nuclear power plant
facilities. As one of the seismic proving tests, shaking table tests for RCCV1 are carried out
using the Tadotsu Engineering Laboratory and the results were reported in a previous paper2).
The objective of this test was to measure the structural integrity and functional soundness of
RCCV’s for both S1 and S2 excitations, and to establish the safety margin by ultimately collapsing
the specimen with extreme shaking to simulate an excessive earthquake.

To understand the response characteristics of the RCCV model during S1 and S2 excitations,
a dynamic simulation analysis with a multi-mass stick model was also conducted as described in section 2.

The analysis is similar to that used in the practical seismic design of commercial nuclear
power plants. Measured horizontal and rotational accelerations at the top of the base mat slab
were used simultaneously as input motion for the analysis. The results appear in section 3.

Also, a performance analysis of the shaking table was conducted in which both the compliance
of the servo system characteristics and the flexibility of base mat were considered. The
content of this analysis is described in section 4.

2. ANALYSIS PROCEDURE

2.1 Analysis Method
The time history nonlinear response analysis method was used for the simulation analysis and is
based on the numerical integration of the dynamic equations of motion using Newmark’s β-
method. Input for the numerical integration came from the shaking table tests. To take into
account the pitching of the shaking table, both the measured horizontal and rotational acceler-
ation were used.
2.2 Mathematical Model
A stick model with multiple mass points was used with a fixed condition at the top of the base mat. Fig.1 shows the analysis model. Material properties of the reinforced concrete and the steel liner used in the model came from material test results. The stiffness of each stick element of the analysis model was evaluated by considering its shearing and flexural deformations. Their nonlinearity were also taken into account for the shell portion.

2.3 Skeleton Curves of Nonlinear Components
Nonlinear characteristics of shell portion stiffness were defined from their shear force(τ)-shear strain(γ) relation (shear skeleton curves) and bending moment-curvature relation (flexural skeleton curves). Each skeleton curve was evaluated based on JEAG\textsuperscript{3} which is used in the practical seismic design of commercial nuclear power plants. Effects of the liner were also considered in the evaluation. Details are summarized in Table 1.

Fig.2 shows the skeleton curve for τ–γ relation (JEAG + Liner Effect) used in the analysis. The tests were conducted through many steps in series with the stiffness of the model decreasing from step to step. Considering these situation, the initial stiffness of each simulation analysis was set to that derived from the corresponding test result. The same reduction factor was applied for shear and flexural stiffness.

General concept of the skeleton curves used in the analysis considering initial stiffness reduction is shown in Fig.3.

2.4 Hysteresis Loops of Nonlinear Components
For hysteresis loops of shear force and shear strain relations, the INADA model\textsuperscript{4} was used which takes into account structural damping and slip effects at small shear stresses. The general concept of the INADA model is shown in Fig.4 and parameters used in the analysis are given in Table 2.

2.5 Damping
Damping values obtained from test results were used in the analysis. These damping values consist of viscous damping, structural damping and plastic deformation damping effects. Viscous damping was assumed to be internal and in proportion to the initial stiffness. Structural damping was given by a parameter of the INADA model, while plastic deformation damping effects came from the skeleton curves and hysteresis loops automatically.

2.6 Analysis Case
Table 3 shows the simulation analysis case. To evaluate the initial stiffness and damping values, frequency transfer functions were obtained and compared to those from the test results before starting each time history nonlinear simulation analysis.

3. ANALYSIS RESULTS

3.1 Frequency Transfer Functions
Frequency transfer functions were obtained and compared to those obtained from test results as shown in Table 4. The peak frequencies and peak heights of the frequency transfer functions matched with those of the test results. Thus we concluded that the initial stiffness and damping values were valid.

3.2 Time History Nonlinear Response Analysis
Time histories of horizontal acceleration at the upper slab obtained by the analysis are compared with test results in Table 5. The hysteresis loops between forces and deformations obtained by the analysis are compared to test results in Table 6.

The time histories of the horizontal acceleration show that the amplitudes from the analysis during high level excitation correspond well with those from the test results.

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Hysteresis loops show that the peak values of shear force from the analysis are slightly larger than those from the test results for S1 level excitations, but this relation is opposite for S2 level excitations. However, the maximum deformations from the analysis are slightly smaller than those of test results for all excitations.

4. PERFORMANCE OF SHAKING TABLE

4.1 Compensation for Target Motion
In general, the input excitation motion for small amplitude shaking table tests follow the following process to obtain the target table motion:
(i) System transfer function acquisition excitement for shaking table and specimen system,
(ii) Iterative compensation excitement.
The flow chart of this process is shown in Fig.5.
This procedure assumes that the specimen has linear dynamic characteristics so that the target table motion can be obtained theoretically.
But for our tests, the input motion level is severe thus producing a fairly large nonlinearity and changing dynamic characteristics during the excitations. So the general compensation procedure mentioned above can not be used. We used about a half level of the target motion for the compensation process to protect the model from damage before main excitation.

4.2 Simulation Analysis of Table Performance
Considering this situation mentioned above, a prediction analysis of the table performance was conducted in which both the compliance of the servo system characteristics and flexibility of the model base mat are taken into account. Mathematical modeling of the compliance of the servo system characteristics was idealized by horizontal and rocking springs. The general concept of base mat flexibility is shown in Fig.6 while the total analysis model is shown in Fig.7.
The simulation analysis was conducted for both S1 and S2 level horizontal excitations. Figs.8, 9 show the response spectra on the table top obtained by tests and analysis, respectively.
The S1 level test result shows large differences from the target. During the excitation, the fundamental natural period of the model changed from 0.08 sec to 0.11 sec because of the model's nonlinearity. The table motion components with the original period (0.08 sec) were amplified, but the nonlinear period components (0.11 sec) were reduced. This phenomenon was predicted by the analysis with base mat flexibility. Note that the analysis result without mat flexibility is different from test results which means that the base mat flexibility has a large influence on the response.
The S2 level test result shows small differences from the target in contrast to the S1 level test results. Before the S2 level excitation, specimen experienced several high stress vibrations and went into the nonlinear range, changes in the fundamental natural period were not as large as that from S1 level excitations. This phenomenon was also predicted by the analysis.

5. CONCLUSION

(1) Simulation analysis results of time histories of horizontal acceleration at upper slab and hysteresis loops between forces and deformations are compared with test results. Simulation analysis results generally agreed with test results from each excitation level. The simulation method is available to apply for prediction analysis of the safety margin tests.
(2) Simulation analysis results which included both the compliance of the servo system characteristics and flexibility in the model base mat predicted the change of fundamental natural period of the model by both S1 and S2 level excitations. The change of the fundamental natural period by S2 level excitations was smaller than that by S1 level excitations. Therefore, the table was controlled better for S2 level excitations than for S1 level excitations. This phenomenon was predicted by the simulation analysis.
ACKNOWLEDGMENT

Since 1980, NUPEC has conducted a series of seismic proving tests of nuclear power plant facilities under the sponsorship of Ministry of International Trade and Industry (MITI) of Japan. The seismic proving test of RCCV is carried out as one of the seismic proving tests. The authors would like to acknowledge the advice of the steering committee of NUPEC.

REFERENCES


Fig. 1 Analysis Model for Horizontal Direction

Fig. 2 Skeleton Curve for $\tau - \gamma$ Relation (JEAG + Liner Effect)

Fig. 3 Skeleton Curves Considering Initial Stiffness Reduction

Fig. 4 Effects of Parameters on INADA Model Hysteresis Loop

Structural Damping Effect

Slip Stiffness Ratio Effect
### Table 1 Estimation of Skeleton Curves

<table>
<thead>
<tr>
<th>Shearing ((\tau - \gamma) relationship)</th>
<th>Bending ((M - \phi) relationship)</th>
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<tr>
<td><img src="image1" alt="Diagram" /></td>
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</table>

**Reinforced concrete**

- **First turning point**
  \[ \tau_1 = \sqrt{f_y (f_y + \sigma_y)} \]

- **Second turning point**
  \[ \tau_2 = \frac{1.35 \cdot f_y}{\sqrt{\sigma_y}} \]

- **Ultimate point**
  \[ \tau_u = \frac{(1 - \varepsilon_s \cdot \varepsilon_y)}{4.5 / f_y} \]

where \(f_y\): compressive strength of concrete [kg/cm²], \(\sigma_y\): tautness of concrete [kg/cm²], \(\varepsilon_s\) and \(\varepsilon_y\): yield stress of concrete [kg/cm²].

- \(\tau_u\): ultimate stress on the reinforcement bar in the stress direction [kg/cm²], \(\varepsilon_u\): ultimate strain of the reinforcement bar in the stress direction.

- \(\varepsilon_s\): yield strain of the reinforcement bar in the stress direction.

- \(\phi\): ultimate angle of the reinforcemnt bar.

- \(f_y\): ultimate stress of the reinforcement bar [kg/cm²].

**Sectional area of liner is included into reinforcing bar ratio at the evaluation of \(M_y\) and \(M_u\) of reinforced concrete by the upper method.**

**Liner**

- **Yield point**
  \[ \tau = \frac{\sigma y_1}{3} \]

- **Ultimate point**
  \[ \tau = \frac{\sigma y_2}{3} \]

\(\sigma = \) N/mm²

\(\sigma y = 306\)

\(\sigma = \frac{E_s \cdot 2.31 \times 10^4}{G_s \cdot 0.89 \times 10^4}\)

\(E_s\): Shear modulus of liner

<table>
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<th>(\sigma)</th>
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### Table 3. Analysis Case (Simulation Model 1)

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<th>Test Before 1</th>
<th>Specimen Characteristic</th>
<th>Analysis</th>
<th>Test Before 1</th>
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### Table 4. Transfer Function

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### Table 2. Parameters of INADA Model Used in the Analysis

- **S**: Strain
- **F**: Force
- **R**: Resistance
- **T**: Temperature
- **n**: Number of cycles
- **m**: Material Property
- **k**: Constant
- **C**: Capacitance
- **L**: Inductance
- **R**: Resistance
- **G**: Conductance
- **B**: Back EMF
- **I**: Current
- **V**: Voltage
- **E**: Electromotive Force
- **P**: Power
- **Q**: Energy
- **W**: Work
- **H**: Entropy
- **S**: Entropy Source
- **T**: Temperature
- **p**: Pressure
- **h**: Enthalpy
- **s**: Entropy
- **u**: Internal Energy
- **w**: Work
- **v**: Volume
- **q**: Heat
- **r**: Resistance
- **g**: Conductance
- **b**: Back EMF
- **i**: Current
- **v**: Voltage
- **e**: Electromotive Force
- **p**: Power
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- **i**: Current
- **v**: Voltage
- **e**: Electromotive Force
- **p**: Power
- **q**: Energy
- **h**: Heat
- **t**: Temperature
Table 5 Comparison of Time Histories of Horizontal Acceleration at Top Slab

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Table 6 Comparison of Hysteresis Loops between Forces and Deformations

<table>
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Analysis of Specimen Characteristic Test

Evaluation of Inverse Transfer Function

Compensation Iteration

Input Motion

Fig. 5 Flow Chart of Compensation Process

Fig. 6 General Concept of Out of Plane Flexibility of Base Mat

Fig. 7 Analysis Model for Horizontal Direction

Fig. 8 Comparison of Response Spectra of Test and Analysis by 1.3 X S1(H)

Fig. 8 Comparison of Response Spectra of Test and Analysis by 1.1 X S2(H)