# Response of Base Isolated Structure during Strong Ground Motions beyond Design Earthquakes

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## ABSTRACT

In Japan, some base isolated structures for fast breeder reactors (FBR) are tried to design. When a base isolated structure are designed, the relative displacement of isolators are generally limited so as to be remain in linear state of those during design earthquakes. But to estimate safety margin of a base isolated structure, the response of that until the failure must be obtained experimentally or analytically during strong ground motions of beyond design earthquake.

The aim of this paper is to investigate the response of a base isolated structure when the stiffness of the isolators hardens and to simulate the response during strong ground motions of beyond design earthquakes. The optimum characteristics of isolators, with which the margin of the structure are increased, are discussed.

## 1 INTRODUCTION

Central Research Institute of Electric Power Industry (CRIEPI) has been doing demonstration test of seismic isolation system for FBR under contract with MITI since 1987[1]. In the study, it has been adopted that the pre-yield natural period of isolators is 1.0 sec, the post-yield natural period is 2.0 sec and the yielding seismic coefficient is 0.05, as the tentative characteristics of isolators. The characteristics have been decided to satisfy the criteria of aseismic design, which are the maximum response acceleration at the support of the reactor vessel and/or the maximum response displacement of the isolators under the design earthquakes (S1 and/or S2).

The aim of this paper is to investigate the response of a base isolated structure when the stiffness of isolators hardens and to simulate the response during strong ground motions of beyond design earthquakes. The optimum characteristics of isolators against strong ground motions including due to beyond design earthquakes are found and discussed by parameter survey.

## 2 NUMERICAL MODEL AND INPUT GROUND MOTIONS

The model of base isolated structure for FBR are lumped mass model of MDOF as shown in Fig.1. The characteristics of the upper-structure, soil, and rotation of layers of isolators are shown in Table 1, 2 and 3.

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The selected models for the hysteresis characteristics of isolators are elasto-plastic model for dampers and hardening restoring model for rubber bearings as shown in Fig.2. The parameters of the hysteresis characteristics are varied to determine the optimum characteristics of isolators under beyond design earthquakes in the range of feasible design values. Varied parameters are post-yield natural period $T_1$, pre-yield natural period $T_d$ and yield load $Q_y$. $T_1$ and $T_d$ are expressed as follows:

$$T_1 = 2\pi\sqrt{m/k_1} \qquad (1)$$

$$T_d = 2\pi\sqrt{m/(k_1+k_d)} \qquad (2)$$

where m, $k_1$ and $k_d$ are mass of total upper-structure, post-yield stiffness and pre-yield stiffness respectively.

Design ground motions are made using the tentative design spectrum for seismic isolation system for FBR[2)] and phase spectrum of observed records, which were observed at La Union (MEX), Mexico in 1985, Shiranuka (SRN) and Furoufushi (FRF), Japan in 1983. Three design ground motions, which are called design ground motion S1, are shown in Fig.3. In order to calculate the responses under beyond design ground motion, the amplitudes of design ground motions are simply magnified.

Varying the parameters of isolators and input levels, 162 cases of calculations were conducted, as shown in Table 4.

## 3 RESULTS OF SIMULATION

The maximum acceleration at the support of the reactor and the maximum displacement of the isolators to each input level are shown in Fig.4, 5 and 6, respectively. The effective parameters on the responses were the yield load, the pre-yield natural period and the post-yield natural period in that order. The effects of parameters to the responses were as follows:

(1) As the yield loads get larger, both the maximum acceleration and the maximum displacement get smaller.

(2) As the pre-yield natural periods get shorter, the responses get smaller.

(3) When the post-yield natural period gets longer (3.0 sec), the maximum displacement increases a little and the maximum acceleration decreases. But it is not necessarily the case in the range of the hardening of the isolators, because the stiffness after hardening is proportional to the post-yield stiffness.

The fluctuation of the responses to different input ground motions were large.

## 4 OPTIMIZATION OF THE CHARACTERISTICS

The characteristics of the isolators have to be optimized to satisfy the aseismic criteria under design input ground motions and to secure the safety margin. The evaluation function or criteria for optimization depends on the design concept of the designers

In this paper, some evaluation functions and criteria are shown to be even to reduce the response acceleration and displacement, as follows:

(1) Evaluating the characteristics with the ranking of the smaller responses, as shown below:

$$E_1(x) = \Sigma(r_{ai}+r_{di}) \qquad (3)$$

where x : parameters of isolators,

$r_{ai}$: the ranking of response accelerations,
$r_{di}$: the ranking of response displacements,
$i$ : number corresponding to each input ground motions.

(2) The evaluation function of normalized responses by the response with the standard parameters (Case 1), as shown below:

$$E_2(x) = \Sigma (a_i/a_{Ni} + d_i/d_{Ni}) \qquad (4)$$

where $a_i$ : the response acceleration at the support of the reactor,
$d_i$ : the displacement of isolators,
$a_{Ni}$ : the response acceleration with the standard parameters,
$d_{Ni}$ : the displacement with the standard parameters

(3) The evaluation function with the mean and the standard deviation of the simulated responses, as shown below:

$$E_3(x) = \Sigma \{(a_i-m_a)/\sigma_a + (d_i-m_d)/\sigma_d\} \qquad (5)$$

where $m_a$ : mean of simulated response accelerations,
$m_d$ : mean of simulated response displacements,
$\sigma_a$ : standard deviation of simulated response accelerations,
$\sigma_d$ : standard deviation of simulated response displacements.

Table 5 shows the results of evaluation with the above evaluation functions in the form of the ranking to reduce the responses in order.

Case 7, 8, 16 and 17 were superior to reduce the responses to the other cases using every evaluation functions. The yield load for all these cases was 0.075W. The more the yield load increases, the more the responses were reduced in the range of the simulation. It was found that shorter pre-yield period was better by the comparison of Case 7 and 8, or case 16 and 17. The effect of the post-yield period did not have the same tendency to the different input ground motions.

## 5 DISCUSSION

The most of the maximum accelerations at the support of the reactor were more than 1.0g in the case of input level $4.0S_1$, so that it may be difficult that all the reactor and other equipment remain safe. But in general, rubber fails at the shear strain of 400 ~ 500%, so that the failure displacement of the isolators in this paper is about 100cm. Though some isolators may fail in the case of input level $4.0S_1$, it is found that the isolators have enough margin at least. Considering the facts that the hysteresis characteristics were simple and the input ground motions were tentative, the above results may not have generality. But the results provide some reference data for the design of the base isolation system.

## 6 CONCLUSIONS

In Conclusion, the results obtained in this paper can be summarized as follows:

(1) It is better selection to reduce the responses of the isolation system that the yield load of isolators is larger and that the pre-yield natural period is shorter, in the range of this simulation.

(2) Some kinds of the evaluation functions were presented. Using the evaluation functions, all the results had the same tendency. The cases which had the larger yield load and the shorter pre-yield natural period were superior to the others. The effect of post-yield natural period did not have the same tendency to the different input ground motions.

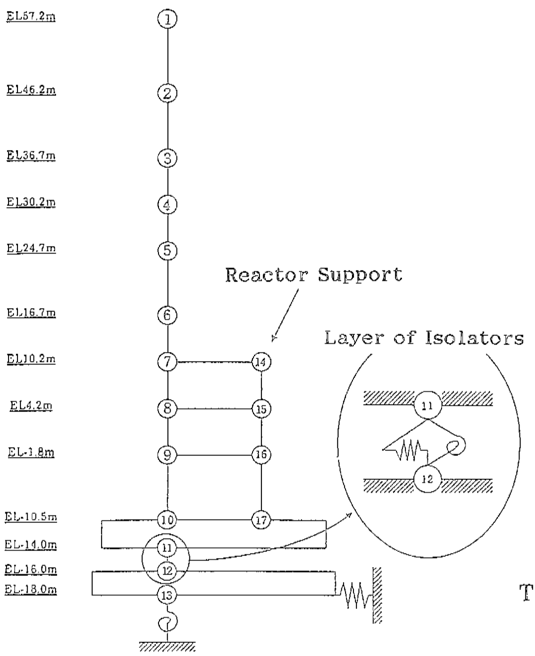
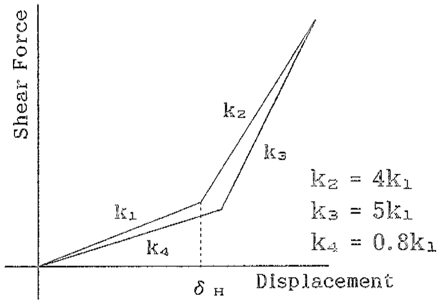
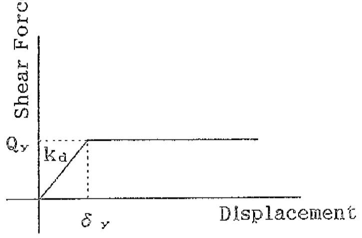


Fig.1 Model of base isolated structure.



(a) Rubber bearings



(b) Dampers

Fig.2 Hysteresis characteristics of rubber bearings and dampers.

Table 1(a) Characteristics of structure.

| Level (m) | No. of Mass | Weight (ton) | Shear Section Area ($\times 10^4 cm^2$) | Moment of Scond Order ($\times 10^{12} cm^4$) | Moment of Inertia ($\times 10^{10} cm^2$) |
|---|---|---|---|---|---|
| EL57.2 | 1 | 2565 | 27.7 | 0.338 | 0.187 |
| EL46.2 | 2 | 2271 | 27.7 | 0.338 | 0.167 |
| EL36.7 | 3 | 2941 | 64.3 | 1.45 | 0.565 |
| EL30.2 | 4 | 5400 | 81.2 | 3.06 | 1.41 |
| EL24.7 | 5 | 11330 | 107. | 5.43 | 2.96 |
| EL16.7 | 6 | 14080 | 130. | 6.25 | 3.68 |
| EL10.2 | 7 | 16220 | 175. | 8.03 | 6.33 |
| EL4.2 | 8 | 16620 | 190. | 8.03 | 4.96 |
| EL-1.8 | 9 | 14570 | 194. | 8.03 | 4.51 |
| EL-10.5 | 10 | 22300 | 3584. | 93.7 | 5.84 |
| EL-14.0 | 11 | 15050 | - | - | 3.94 |
| EL-16.0 | 12 | 10420 | 4340. | 139. | 3.34 |
| EL-18.0 | 13 | 10420 | | | 3.34 |

Table 1(b) Characteristics of the support structure of the reactor.

| Level (m) | No. of Mass | Weight (ton) | Shear Section Area ($\times 10^4 cm^2$) | Moment of Scond Order ($\times 10^{12} cm^4$) | Moment of Inertia ($\times 10^{10} t cm^2$) |
|---|---|---|---|---|---|
| EL10.2 | 14 | 7950 | 66.3 | 0.699 | 0.390 |
| EL 4.2 | 15 | 2330 | 66.3 | 0.699 | 0.108 |
| EL-1.8 | 16 | 2660 | 66.3 | 0.699 | 0.124 |
| EL-10.5 | 17 | - | | | - |

Table 1(c) Characteristics of material

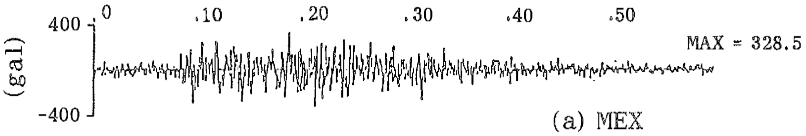
| | Elastic Modulus ($t/cm^2$) | Shear Elastic Modulus ($t/cm^2$) | Weight per Unit Volume ($\times 10^6 t/cm^3$) | Damping Ratio |
|---|---|---|---|---|
| Concrete | 230 | 98.6 | 2.40 | 0.05 |

Table 2 Characteristics of soil. (Vs = 1500 m/sec)

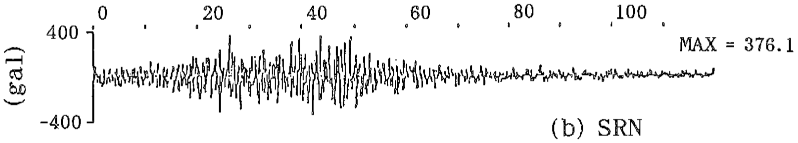
| | Spring Constant | Coefficient of Damping |
|---|---|---|
| Horizontal Spring | t/cm<br>$K_h = 9.16 \times 10^5$ | t·sec/cm<br>$C_h = 1.24 \times 10^4$ |
| Rotational Spring | t·cm/rad<br>$K_\theta = 9.87 \times 10^{12}$ | t·cm·sec/rad<br>$C_\theta = 1.95 \times 10^{10}$ |

Table 3 Rotational characteristics of isolators.

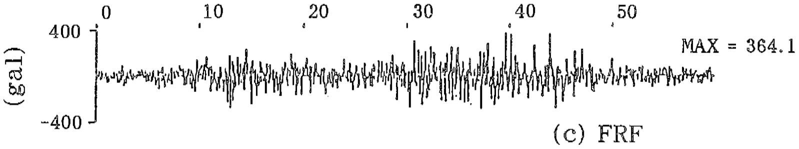
| Rotational Spring Conatant | Dmping Ratio |
|---|---|
| $K_\theta = 6.74 \times 10^{12}$ t·cm/rad | 0.02 |



(a) MEX



(b) SRN



(c) FRF

Fig.3 Input ground motions (1.0 S1).

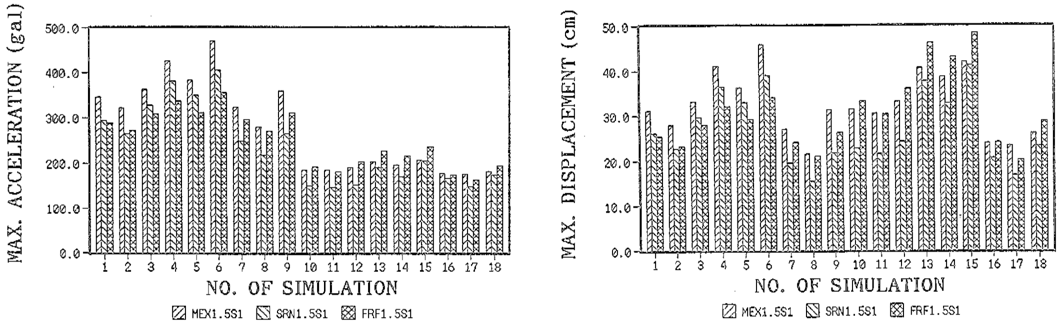
Table 4 Simulated Cases.

| No. of Simulation | Post-yield Natural Period (sec) | Pre-yield Natural Period (sec) | Yield Load | Input | Magni-fication of input |
|---|---|---|---|---|---|
| M - 1.5 - 1<br>(S) (3.0)<br>(F) (4.0) | 2.0 | 1.0 | 0.050W | MEX<br>SRN<br>FRF | 1.5<br>(3.0)<br>(4.0) |
| 2 | 2.0 | 0.82 | 0.050W | | |
| 3 | 2.0 | 1.15 | 0.050W | | |
| 4 | 2.0 | 1.0 | 0.025W | | |
| 5 | 2.0 | 0.82 | 0.025W | | |
| 6 | 2.0 | 1.15 | 0.025W | | |
| 7 | 2.0 | 1.0 | 0.075W | | |
| 8 | 2.0 | 0.82 | 0.075W | | |
| 9 | 2.0 | 1.15 | 0.075W | | |
| 10 | 3.0 | 1.0 | 0.050W | | |
| 11 | 3.0 | 0.82 | 0.050W | | |
| 12 | 3.0 | 1.15 | 0.050W | | |
| 13 | 3.0 | 1.0 | 0.025W | | |
| 14 | 3.0 | 0.82 | 0.025W | | |
| 15 | 3.0 | 1.15 | 0.025W | | |
| 16 | 3.0 | 1.0 | 0.075W | | |
| 17 | 3.0 | 0.82 | 0.075W | | |
| 18 | 3.0 | 1.15 | 0.075W | | |

W : Weight of the Upper-structure

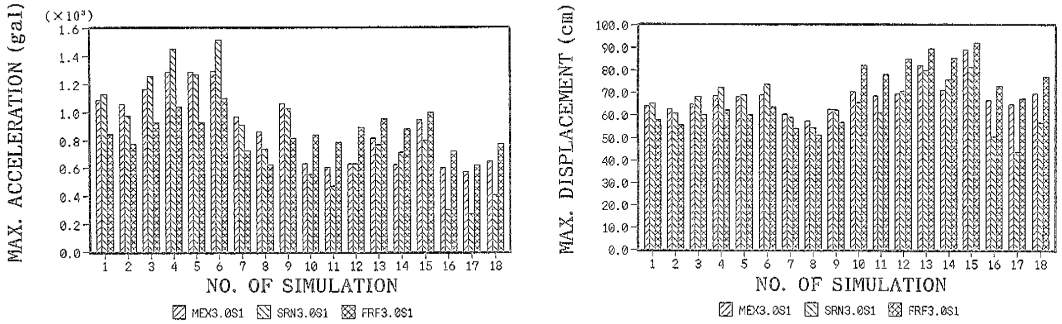
Table 5 Ranking of evaluation with each evaluation function.

| No. of Simula-tion | $E_1$ | | | $E_2$ | | | $E_3$ | | |
|---|---|---|---|---|---|---|---|---|---|
| | MEX | SRN | FRF | MEX | SRN | FRF | MEX | SRN | FRF |
| 1 | 12 | 12 | 6 | 14 | 14 | 5 | 12 | 12 | 6 |
| 2 | 6 | 9 | 3 | 11 | 12 | 2 | 10 | 8 | 4 |
| 3 | 14 | 16 | 11 | 15 | 15 | 8 | 13 | 14 | 8 |
| 4 | 17 | 17 | 13 | 17 | 17 | 12 | 15 | 17 | 13 |
| 5 | 15 | 14 | 9 | 16 | 16 | 9 | 14 | 15 | 9 |
| 6 | 18 | 18 | 16 | 18 | 18 | 13 | 17 | 18 | 15 |
| 7 | 5 | 7 | 4 | 9 | 11 | 4 | 6 | 7 | 2 |
| 8 | 2 | 5 | 1 | 7 | 9 | 1 | 2 | 5 | 1 |
| 9 | 11 | 11 | 7 | 13 | 13 | 6 | 11 | 10 | 5 |
| 10 | 8 | 6 | 12 | 5 | 5 | 14 | 8 | 6 | 12 |
| 11 | 4 | 3 | 10 | 4 | 3 | 11 | 4 | 4 | 11 |
| 12 | 10 | 8 | 14 | 6 | 6 | 15 | 5 | 9 | 16 |
| 13 | 13 | 13 | 17 | 10 | 8 | 17 | 16 | 13 | 17 |
| 14 | 9 | 10 | 15 | 8 | 7 | 16 | 9 | 11 | 14 |
| 15 | 16 | 15 | 18 | 12 | 10 | 18 | 18 | 16 | 18 |
| 16 | 3 | 2 | 5 | 2 | 2 | 7 | 3 | 2 | 7 |
| 17 | 1 | 1 | 2 | 1 | 1 | 3 | 1 | 1 | 3 |
| 18 | 7 | 4 | 8 | 3 | 4 | 10 | 7 | 3 | 10 |



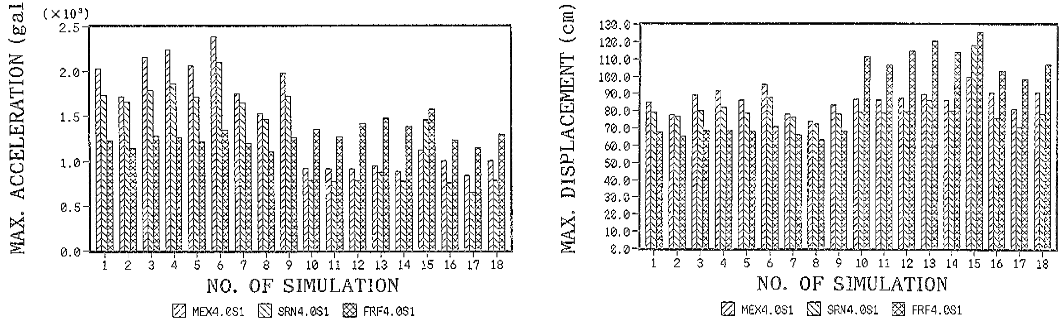
(a) Max. acceleration at reactor support (b) Max. displacement of isolators

Fig.4 Maximum responses of each simulated case (1.5 S1).



(a) Max. acceleration at reactor support (b) Max. displacement of isolators

Fig.5 Maximum responses of each simulated case (3.0 S1).



(a) Max. acceleration at reactor support (b) Max. displacement of isolators

Fig.6 Maximum responses of each simulated case (4.0 S1).

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1) Y.Sawada et al.,"Seismic Isolation Test Program",Trans. of 10th SMiRT(1989), Vol.K2, pp.691-696.
2) K.Ishida et al.,"Tentative Design Response Spectrum for Seismically Isolated FBR",Trans. of 10th SMiRT(1989), Vol.K2, pp.685-690.