Probabilistic Assessment on Torsional Vibration of a Base Isolated Structure for FBR

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INTRODUCTION

Recently, electric power industry, universities and manufacturers discuss to introduce a base isolation system into a fast breeder reactor plant (FBR), because seismic load is more dominant and, maybe, critical than the other loads in the design of FBR. In some trial design of a base isolated structure for a large-scale FBR, several hundred pads are used. The pads' characteristics may not be uniform, because of randomness caused by the aging and other reasons. If the distribution of pads' characteristics is uneven, torsional vibration of super-structure shall occur during an earthquake. The torsional vibration may give some additional damage to the reactor vessel, piping and other equipment.

Base isolation system is generally inelastic system. Torsional response of inelastic system was studied by some researchers, but one of the system in which inelastic elements have random characteristics is investigated here. The aim of this paper is to investigate the relation to the randomness of pads' characteristics and the torsional vibration using Monte Carlo method, and to obtain the basic idea to decide the range of randomness of their characteristics for design guide of an isolation system.

3DOF MODEL OF THE ISOLATED STRUCTURE

As shown in Fig.1, the isolated structure is modeled as 3DOF hysteretic system which consists of a rigid slab and pads. The restoring characteristics of each pad is bi-linear with circular yielding curve, which is modeled on a lead rubber bearing. In elastic state, stiffness is always the first stiffness k_1, and in plastic state (Fig.2), tangent stiffness is shown as,

$$k_x = k_1 \{(\gamma-1)\cos\theta(\cos\theta + \frac{dy}{dx}\sin\theta) + 1\} \qquad (1)$$

$$k_y = k_1 \{(\gamma-1)\sin\theta(\sin\theta + \frac{dx}{dy}\cos\theta) + 1\} \qquad (2)$$

where γ is ratio of first and second stiffness.

For the simulation, the model was chosen as follows: mean of k_1 and γ are decided so that mean natural frequency of this system in horizontal direction is 1.3 Hz in elastic state and 0.5 Hz in plastic state. Mean of displacement at yielding point is set so that a pad subjected to 50 gal input yields.

MONTE CARLO SIMULATION

As there is no statistical data on the randomness of pads' characteristics by the aging, the distribution of the randomness is assumed log-normal distribution. In each sample of Monte Carlo simulation, the first stiffness and/or the yielding displacement of each pad is given randomness in order to simulate the uneven distribution of the characteristics. Trial number of the simulation was decided to be 50 samples by the convergence of the mean and the standard deviation of maximum torsional angle. The inputs are two directional ground motions. Two sets of input ground motions chosen for the simulation are NS and EW components of time histories recorded at El Centro in 1940 (max. acc. NS: 341.7 gal, EW: 210.1 gal) and at Hachinohe, Japan in 1968 (max. acc. NS: 225.0 gal, EW: 182.9 gal).

In a model of a large FBR with a lot of pads, the amount of the calculation is very large, so that two types of isolated structure model are discussed. First, the basic relations between the maximum torsional angle and the variation of the pads' characteristics are discussed with the partial model as shown in Fig.3. In this case, number of pads is changed from 9 to 36, and the range of randomness of pads' characteristics, or the coefficient of variation (COV) is changed from 10% to 40%. Secondly, actual torsional vibration of the isolated structure is estimated with an actual size model. Fig.4 shows an actual size model of the base isolated structure for FBR. Number of pads is 16, 100 and 256. The COV of their pads' characteristics is set 40%. Wilson θ method is used with θ = 1.4, and time interval for the simulation is 1 msec (partial model) and 2.5msec (actual model).

RESULTS OF SIMULATION

Simulation for Partial Model of the Base Isolated Structure

The responses at the center of gravity are almost equal to all cases. The relation between the mean of maximum torsional angle and the variation of the stiffness and yielding displacement is shown in Figs.6. The mean of maximum torsional angles is proportional to the variation. The COV of the maximum torsional angles is constant to the variation of the pads' characteristics. The maximum torsional angle in the case of random stiffness is about twice as big as one in the case of the random yielding displacement. That is, the variation of the stiffness is more effective to excite the torsional vibration than one of the yielding displacement. In the case that both the stiffness and the yielding displacement are given randomly, the maximum torsional angle is less than sum of those which occur where their randomnesses are independently given.

The mean of maximum torsional angles decreases according to increasing the number of the pads as shown in Table 1. It is found that the mean of maximum torsional angle is proportional to distance of the eccentric center which is the distance between the center of gravity and the center of torsion in elastic state. The normalized distance of eccentric center, based on where the number of pads is 9, is almost as same as normalized maximum torsional angle, so that maximum torsional angle in the case of multi-pads can be estimated by the result of the maximum torsional angle for 9 pads obtained by Monte Carlo simulation. The estimated torsional angle a_e for other cases can be written as

$$a_e = a_s e \qquad (3)$$

where a_s : the maximum torsional angle calculated by Monte Carlo simulation for 9 pads in normalizing number,
e : normalized distance of eccentric center based on 9 pads for other multi-pad cases.

The authors call this method the simplified estimation method.

By using two sets of input ground motions, the distributions of maximum torsional angles are different, as shown in Fig.6. Although the peak acceleration of Hachinohe waves are smaller than those of El Centro, the torsional responses are almost same. This reason may be that Hachinohe waves include long period components.

Simulation for Actual Size Model

The maximum responses are shown in Table 2, in the case that the stiffness is given randomness. Horizontal acceleration is reduced by about 1/3 to input ground motion. The mean of maximum torsional accelerations and angles are 3.0×10^{-3} rad/sec^2 and 1.2×10^{-4} rad, so that the incremental acceleration and displacement at the corner of the slab are about 10 gal and 3 cm. Considering to add the variation of the responses to the mean, these values are not large. Table 3 shows relation between number of pads and distance of the eccentric center. Table 4 shows the comparison of the maximum torsional angles estimated by the simplified method from normalized distance of the eccentric center and those obtained by Monte Carlo simulation. They are almost consistent, so that the simplified estimation method can be said to be verified.

The shear buckling of a reactor vessel in a pool type large FBR plant, as shown in Fig.7, is examined, as an example of the effect of torsional response of the building to the equipment of FBR. The maximum stress of the vessel section at the upper edge is 3.0×10^{-4} kg/mm^2, when the maximum torsional acceleration is 3.0×10^{-3} rad/sec^2 in COV of stiffness 40%. In spite of large limit variation of their characteristics, the maximum stress is much smaller than the limit of its shear buckling stress.

CONCLUSIONS

The torsional vibration of a base isolated structure for FBR caused by the aging of pads was simulated by Monte Carlo method, and the relation between the torsional vibration and the variation of pads was investigated. The following results from the simulation for several levels of model are obtained:

(1) The mean of the maximum torsional angles is proportional and the coefficient of their variation is almost constant to the variation of the stiffness and yielding displacement.

(2) The randomness of the stiffness is more effective to excite the torsional vibration than that of yielding displacement.

(3) The maximum torsional angle degreases according to increasing the number of the pads, and is proportional to the distance of the eccentric center. From this result, the simplified estimation method of maximum torsional angle has been presented.

(4) Using two sets of input ground motions, the distributions of maximum torsional angles are different. Hachinohe waves which include long period component, tend to excite more the torsional vibration response.

In the actual size model, the torsional response is small, so that the reactor vessel in pool type FBR may not suffer damage. Through applying to the actual size model, the simplified estimation method of the maximum torsional angle was verified.

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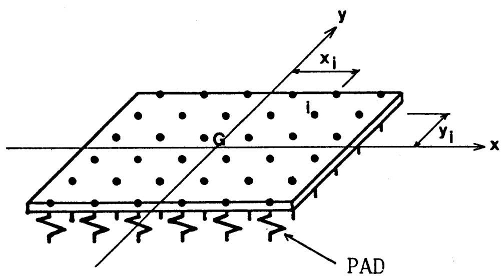


Fig.1. Isolated Structure Model

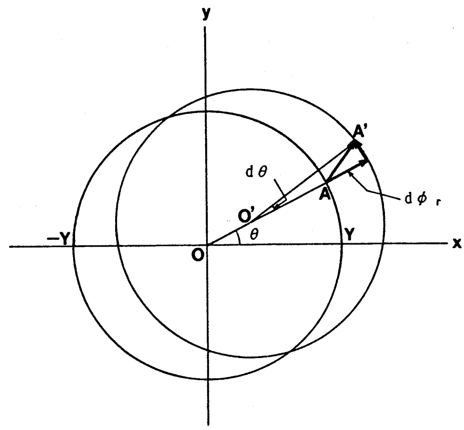
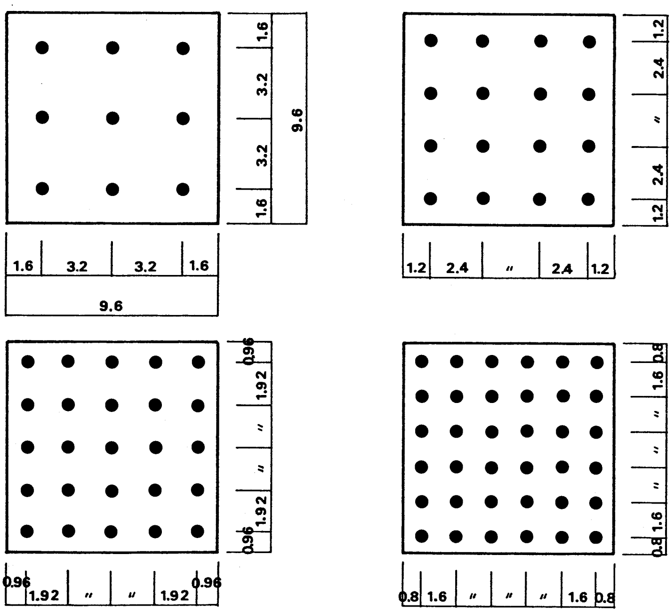
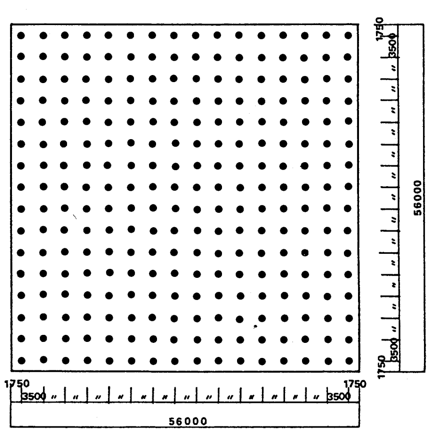


Fig.2. Yielding Displacement Circle



Weight of Slab : 4,500ton

Fig.3. Partial model



Weight of Slab : 128,000ton
Number of Pads : 256

Fig.4. Actual Size Model

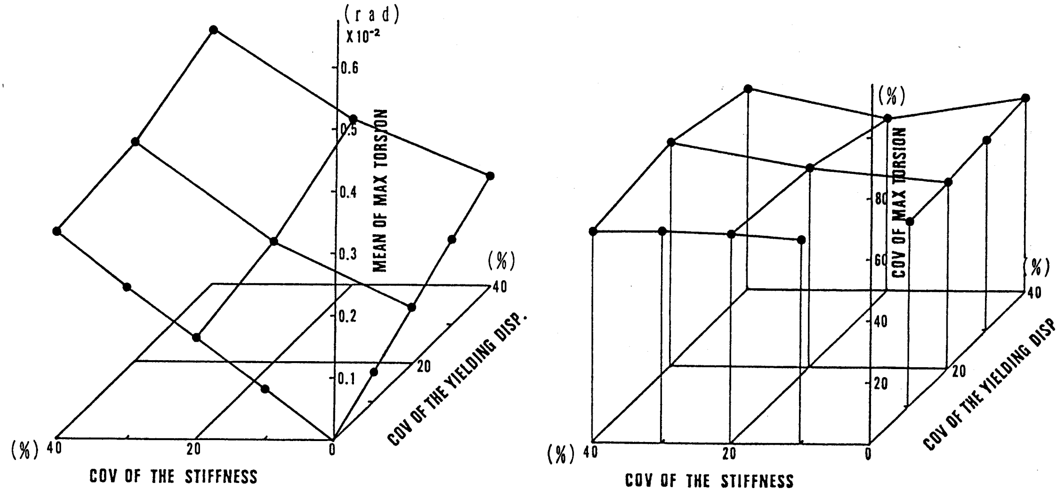


Fig.5. Relation Between Maximum Torsional Angle and Variation of Pads' Characteristics (Input: El Centro, Number of Pads: 9)
(a) Mean of Maximum torsional Angles (b) COV of Maximum torsional Angles

Table 1. Normalized Distance of Eccentric Center *v.s.* Normalized Maximum Torsional Angle (COV of Stiffness : 40%)

Pad No.	9	16	25	36
Dis. of Ecc. Center (cm)	40.31	34.62	26.28	22.45
Normalized Dis. of Ecc. Center	1.0	0.86	0.65	0.56
El Centro: Norm. Max. Tor. Angle	1.0	0.82	0.61	0.49
Hachinohe: Norm. Max. Tor. Angle	1.0	0.72	0.55	0.46

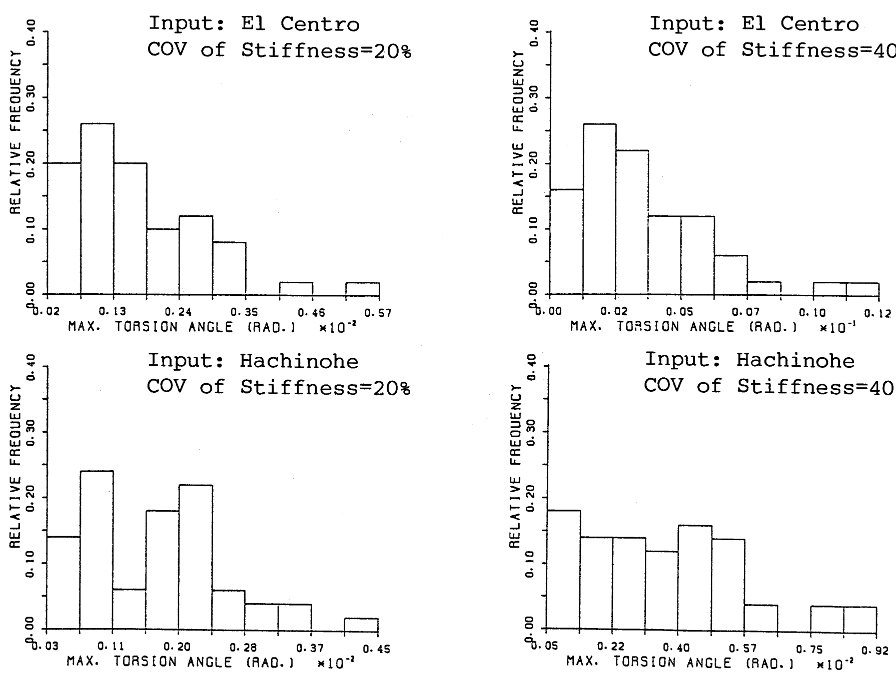


Fig.6. Distribution of Maximum Torsional Angle

Table 2. Maximum Responses of Actual Size Model
(Input: El Centro, COV of Stiffness= 40%)

Pad No.		16	100	256
Max. Acc. at Gravity Center (gal)	x	117.877 3.636	117.508 0.829	117.381 0.492
	y	109.269 4.158	109.636 1.948	109.680 1.159
Max. Disp. at Gravity Center (cm)	x	7.885 0.829	7.636 0.378	7.590 0.225
	y	7.703 0.810	7.569 0.326	7.551 0.188
Max. Acc. at Slab Corner (gal)	x	124.625 5.225	119.973 1.862	119.106 1.247
	y	112.806 4.896	110.815 1.953	110.654 1.757
Max. Disp. at Slab Corner (cm)	x	8.564 1.144	7.877 0.511	7.757 0.269
	y	8.653 1.178	7.870 0.454	7.758 0.235
Max. Torsional Acc. (rad/s^2)		0.976×10^{-2} 0.419×10^{-2}	0.502×10^{-2} 0.283×10^{-2}	0.354×10^{-2} 0.184×10^{-2}
Max. Torsional Disp. (rad)		0.502×10^{-3} 0.327×10^{-3}	0.177×10^{-3} 0.114×10^{-3}	0.124×10^{-3} 0.725×10^{-4}

Upper Values: Mean, Lower Values: Standard Deviation

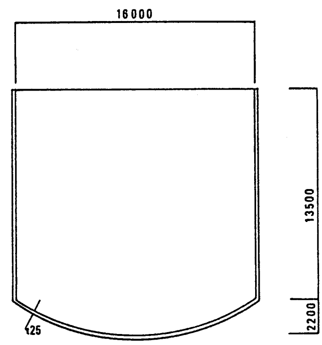


Fig.7. An Example of Schematic Drawings of Reactor Vessel in a Fast Breeder Reacter Vessel

Table 3. Distance of Eccentric Center for Actual Size Model

Pad No.	16	100	256
Dis. of Ecc. Center (cm)	202.0	77.5	51.9
Normalized Dis. of Ecc. Center	1.0	0.384	0.257

Table 4. Estimated Maximum Torsional Angle by Monte Carlo Simulation and Simplified Estimation Method

Input	Pad No.	16	100	256
El Centro	Monte Carlo Sim. (rad)	5.02×10^{-4}	1.77×10^{-4}	1.24×10^{-4}
	Simplified Estimation(rad)	—	1.93×10^{-4}	1.29×10^{-4}
Hachinohe	Monte Carlo Sim. (rad)	5.11×10^{-4}	1.80×10^{-4}	1.18×10^{-4}
	Simplified Estimation(rad)	—	1.96×10^{-4}	1.31×10^{-4}