Torsional Response Behavior of Base-Isolated FBR Reactor Building During Earthquake Excitation*

Kaoru MIZUKOSHI**, Yasuaki FUKUSHIMA**,
Yasuo TAKENAKA**, Masafumi NARIKAWA***,
Manabu MADOKORO**** and Yutaka KAWAMURA*****

This paper describes an analytical evaluation of the effect of torsional motion on seismic responses of base-isolated FBR buildings which were designed conceptually in an applicability study of base isolation systems. Dynamic response coupling with torsional motion induced by obliquely incident earthquake input and by eccentricity in the structure was evaluated by response analyses, taking the biaxial nonlinearity of base isolation devices into account. As a result, it is shown that the effect of the torsional motion on the response of the building, devices, and the floor response spectra is not so large from a seismic design standpoint.

Key Words : Seismic Motion, Nonlinear Vibration, Base Isolation, Reactor Building, Torsional Behavior, Obliquely Incident Wave, Eccentricity

1. Introduction

A drastic reduction in seismic response can be attained by applying a base isolation system to stiff structures such as nuclear power plant buildings, and the aseismic capability of the building structure and of equipment installed in the building can be improved. Especially for pool-type LMFBR reactor buildings constructed in areas of high seismicity, the introduction of a base isolation system can bring great benefits because the seismic load is a very important factor in the design of the primary vessel. However, the safety

and reliability of the system should be checked and studied carefully from various viewpoints.

As part of the applicability study, two types of base-isolated LMFBR building were designed conceptually, and the torsional response behavior of these buildings induced during an earthquake was investigated analytically. The torsional response is generally due to several causes. Irregularity of the ground, Love's wave, or obliquely incident SH waves may generate torsional earthquake input in the foundation of the building. Moreover, eccentricity of the center of mass from the center of rigidity in the horizontal plane may also induce torsional motion even under translational earthquake excitation. Such eccentricity may be caused by an irregular distribution of stiffness and mass, stiffness imperfection, nonlinearity of structural elements, and so on.

In this paper, the seismic response coupled with torsional motion induced by obliquely incident SH wave input and mass-rigidity eccentricity is evaluated by conducting dynamic response analyses, taking account of the biaxial nonlinear characteristics of base isolation devices. Then the effect of the torsional motion on the response of the building, on the defor-

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** Kajima Corporation, Tobitakyu 2-19-1, Chofu, Tokyo 182, Japan

*** Nuclear Power Research & Development, The Tokyo Electric Power Company Inc., Uchisaiwaicho 1-1-3, Chiyoda-ku, Tokyo 100, Japan

**** Advanced Reactor & Nuclear Fuel Cycle Development, Hitachi Works, Hitachi Corporation, Saiwai-cho 3-1-1, Hitachi, Ibaraki 317, Japan

***** Advanced Reactor Engineering Development, Toshiba Corporation, Shinsugitacho 8, Isogo-ku, Yokohama 235, Japan

Fig. 1 Base-isolated LMFBR buildings

mation of the devices and on the floor response spectra is discussed.

2. Base-Isolated Reactor Buildings

Two conceptually designed pool-type LMFBR buildings, A and B, as shown in Fig. 1, are the objects of this study. In building A, the entire reactor building is isolated from horizontal earthquake motion by base isolation devices between the lower and upper base mats. The devices, which are composed of laminated rubber bearings and hysteretic dampers, are designed so as to have bilinear restoring force characteristics in the lateral direction and to have sufficiently high stiffness in the vertical direction. Reduction of lateral seismic force can be attained satisfactorily by this popular type of base isolation (Ref. (1)). On the other hand, in building B, an advanced seismic isolation concept is applied. The nuclear steam supply system (NSSS) floor is isolated vertically using steel coil springs and viscous dampers (Ref. (2)) in addition to horizontal base isolation of the building using the same devices as in building A between the underground story and the upper base mat, as shown in Fig. 1. The NSSS floor, which includes the primary vessel and the core, is isolated three-dimensionally from earthquake excitation.

3. Torsional Behavior due to Obliquely Incident SH Wave Input

3.1 Input ground motion

When an obliquely incident SH wave travels in the ground, as shown in Fig. 2, the horizontal displacements on the ground surface at different points are not in phase in the travelling direction, and a rigid foundation resting on the ground undergoes torsional motion in addition to translational motion. The extent of

Fig. 2 Building A in obliquely incident earthquake

torsional motion depends on the incident angle, ground rigidity, and foundation size. The response of building A subjected to such obliquely incident SH wave input is analyzed in accordance with the procedure for the dynamic substructure method. Firstly, the translational and torsional motions of a rectangular rigid foundation without mass resting on the ground surface and having the same size as the lower base mat of building A are computed. Then, dynamic response analyses are carried out using a structure model with soil springs under translational and torsional excitation conditions.

The parameters considered in analyses A-1 to A-5 are the incident angle α (0 to 90°) and the shear wave velocity of the ground V_s (400 to 1500 m/s), as listed in Table 1. El Centro 1940 NS ($A_{\max} = 341.7$ Gal, Fig. 3) is used as the incident SH wave.

When a massless rigid foundation of size $l_x \times l_y$ resting on the surface of homogeneous ground with shear wave velocity V_s is subjected to an SH wave

with an incident angle α to the vertical z -axis, the translational and torsional transfer functions of the foundation, $F_y(\omega)$ and $F_\theta(\omega)$, can be evaluated by the following equations with fairly good approximation (Ref. (3)).

$$F_y(\omega) = \frac{\sin(a_0 \sin \alpha)}{a_0 \sin \alpha}$$

$$F_\theta(\omega) = i \frac{6lx}{(lx^2 + ly^2)} \left\{ \frac{\cos(a_0 \sin \alpha)}{a_0 \sin \alpha} - \frac{\sin(a_0 \sin \alpha)}{(a_0 \sin \alpha)^2} \right\}$$

$$a_0 = \omega lx / 2 V_s$$

The transfer functions calculated for each case are shown in Fig. 4. Although the peaks of the torsional component move to the lower frequency side with lower shear wave velocity and larger incident angle, they do not reach the fundamental sway frequency of the building (0.5 to 1.0 Hz). Input motions to the structure model are calculated by multiplying the El Centro wave by these transfer functions in the frequency domain.

Table 1 Analysis cases

Case	A-1	A-2	A-3	A-4	A-5
V_s of ground (m/s)	700	700	700	400	1500
Incident angle α	0°	45°	90°	90°	90°

Fig. 3 SH wave U_0 (El Centro 1940 NS)

Fig. 4 Transfer functions of foundation on ground surface

3.2 Structure model

The superstructure and lower base mat of building A are modeled as the multiple lumped-mass model shown in Fig. 5. Each node has two horizontal (X, Y) and three rotational ($\theta_x, \theta_y, \theta_z$) degrees of freedom. The floor slabs and base mats are assumed to be rigid and no eccentricity of mass or rigidity exists in this structure model. The base isolation devices are reduced to sixteen (4×4) nonlinear elements arrayed between the upper and lower base mats. These nonlinear elements are modeled on Prager's kinematic hardening rule (Ref. (4)) and can represent biaxial nonlinear behavior of hysteretic dampers. The impedance of the lower base mat on the ground are evaluated in terms of sway, rocking, and torsional soil springs by a three-dimensional wave propagation theory. Nonlinear dynamic analyses of this structure model with simultaneous input of translational (Y) and torsional (θ_z) motions were carried out by the direct integration method.

3.3 Results of analysis

The eigenvalues of the structure model, when $V_s = 700$ m/s, are listed in Table 2. The first torsional mode has almost the same frequency as that of the first translational mode.

In the dynamic analyses, the maximum response of the building, the maximum deformation of the devices, and the floor response spectra at the supporting level for the primary vessel shown in Fig. 6 to 8

Fig. 5 Analysis model for building A

were obtained. These results can be summarized as follows:

(a) An increase in the incident angle of the SH wave and a decrease in the shear wave velocity of the ground causes a larger torsional response of the building. However, the maximum torsional acceleration is

reduced to 0.2 to 0.4 times the maximum torsional input acceleration. Translational acceleration is almost unchanged.

(b) The incident angle and shear wave velocity also effect the deformation in the isolation layer. The torsional deformation combined with sway deformation results in a difference in the deformation of the devices, depending on their location. The largest difference in device deformation between the center and the fringe of the base mat is about 20% when $\alpha = 90^\circ$ and $V_s = 400$ m/s.

(c) The effect of the incident angle and shear wave velocity on the floor response spectra is relatively small. The difference in floor response spectra at the level of the primary vessel support due to location is 30% at most in the period range shorter than 0.3 s,

Table 2 Eigenvalues of structure ($V_s = 700$ m/s)

Mode	Frequency	β_x	β_y	β_z	Note
1	0.966	1.163	0.0	0.0	X direct. 1st
2	0.968	0.0	1.142	0.0	Y direct. 1st
3	1.011	0.0	0.0	1.052	Torsion 1st
4	3.437	0.212	0.0	0.0	Y direct. 2nd
5	3.677	0.0	0.184	0.0	Y direct. 2nd
6	5.773	0.056	0.0	0.0	X direct. 3rd
7	6.098	0.0	0.0	0.075	Torsion 2nd

Fig. 6 Maximum response values at center of building A

Fig. 7 Maximum lateral deformation of isolation devices

Fig. 8 Floor response spectra at PV supporting level

which is important in major equipment design.

4. Torsional Behavior Due to Eccentricity

4.1 Eccentricity

The eccentricity of mass and rigidity in a structure also induces the torsional response during a translational earthquake. The effect of eccentricity in building B is discussed in this section. Two types of eccentricity, E_s and E_b , are considered as parameters. Type E_s denotes the mass-rigidity eccentricity within the superstructure, which is supported by isolation devices, while E_{so} is the eccentricity evaluated from the conceptual design of building B. Type E_b denotes eccentricity at the isolation layer, that is, the deviation of the rigidity center of all the base isolation devices from the mass center of the entire superstructure. The values of E_b in this study are assumed to be 0%, 2%, 5% and 10% of the width of the upper base

Fig. 9 Analysis model for building B

mat, while the actual value of E_b evaluated for building B is 0.72%. El Centro 1940 NS is used again as the translational input earthquake. Table 3 shows the analytical cases from B-1 through B-6.

4.2 Analysis model

Building B is modeled as a multiple lumped-mass model with soil springs and sixteen biaxial nonlinear elements in the same manner as the modeling of building A. Mass-rigidity eccentricity is expressed in the model as the deviated lumped masses and three dimensional beam elements, which are connected with the nodes located at the center of the base mat by using perfectly rigid elements. Figure 9 shows the configuration of this model and the coordinates of the center of mass and rigidity at each floor level. Since

Table 3 Analysis cases

Case	B-1	B-2	B-3	B-4	B-5	B-6
E_s	0 %	0 %	0 %	0 %	E_{so}	E_{so}
E_b	0 %	2 %	5 %	10 %	0 %	5 %

Table 4 Eigenvalues ($E_b=10\%$, $E_s=0\%$)

Mode	Frequency	Participation factor		Note
		β_x	β_y	
1	0.929	0.0	0.981	Y direct. 1st
2	1.018	1.396	0.0	X direct. 1st
3	1.215	0.0	0.559	Torsion 1st
4	1.970	0.0	0.562	Y direct. 2nd
5	2.200	0.417	0.0	X direct. 2nd
6	3.660	0.0	0.007	Torsion 2nd

Fig. 10 Maximum response values at center of building B

the X -directional deviation is predominant in building B, Y -directional seismic excitation is considered and X -directional eccentricity of isolation layer Eb is assumed in the analyses.

4.3 Results of Analysis

The eigenvalues, when the deviation of Eb is 10% and when there is no eccentricity of Es, are listed in Table 4. The maximum acceleration and displacement at the center are plotted for each case in Fig. 10. Figure 11 shows the floor response spectra. Figure 12 shows a typical behavior of the biaxial nonlinear element for the devices. The maximum lateral defor-

mations of base isolation devices at the center and at the fringe are plotted for each case in Fig. 13. These results for the nonlinear dynamic analyses can be summarized as follows:

(a) The eccentricity in the superstructure, Es, induces the torsional response of the building to some extent, but the influence on the maximum deformation of the base isolation devices is small.

(b) The eccentricity of the isolation layer, Eb, also causes the torsional coupling with the response of the building and increases the maximum deformation of the devices located at the fringe of base mat almost

Fig. 11 Floor response spectra at NSSS floor supporting level

Fig. 12 Hysteresis of horizontal isolation device at the fringe

Fig. 13 Maximum lateral deformation of horizontal isolation devices

in proportion to the eccentric distance. When the deviation is 10%, for example, the maximum deformation increases to 1.2 times that without eccentricity.

(c) When the torsional motion is coupled, the floor response spectra at the fringe of the building tend to be larger than those at the center. As for the effect of E_s , the difference in the spectra appears only around the period of the second mode and is small. On the other hand, the difference due to E_b appears in the wide range of the period but is 30% at most in the significant period range for equipment design shorter than 0.3 s, even with accidental eccentricity at 10%.

5. Conclusion

The torsional seismic response of base-isolated LMFBR buildings due to the obliquely incident SH wave input and mass-rigidity eccentricity has been computed by nonlinear dynamic analyses. Its effect on seismic response was observed at various parts of the structure and equipment. However, the analytical results prove that such induced torsional response does not greatly affect the aseismic capability of a base-isolated reactor building from an aseismic design standpoint. That is, the torsional input due to obliquely incident waves is small in the case of reactor

buildings on rock sites and the response reduction effect achieved by base isolation is also valid for the torsional earthquake input. The eccentricity of the building has no significant influence, provided that the eccentricity at the isolation layer is controlled properly in the design process.

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