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Effects of High Damping Rubber Bearing on Horizontal and Vertical Seismic Responses of a Pressurized Water Reactor

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Abstract

The seismic responses of a base isolated Pressurized Water Reactor (PWR) are investigated using a mathematical model which expresses the superstructure as lumped mass-spring model and the seismic isolator as an equivalent spring-damper. Time history analyses are performed for the 1940 El Centro earthquakes in both horizontal and vertical directions. In the analysis, structural damping of 5% is used for the superstructure. The isolator damping ratios of 12% for horizontal and 5% for vertical directions are used. The acceleration responses in base isolated PWR superstructure with high damping rubber bearings are much smaller than those in fixed base structure in horizontal direction. However, the vertical acceleration responses at the superstructure in the base isolation system are amplified to some extent. It is suggested that the vertical seismic responses at the superstructure should be reduced by introducing a soft vertical isolation device.

1. Introduction

The seismic isolation systems used for the reduction of the seismic response of the structures are now practically applied in Japan, USA, New Zealand, Italy, China, and etc. where large earthquakes were occurred. In our country a seismic isolation system was applied for LNG tanks, and authors have tried to established the seismic isolation design for nuclear reactors[1,2,3]. The horizontal seismic isolation systems are usually designed to lower the fundamental frequency of structure in the range of 0.5Hz to 0.7Hz, which prevents the structural damage from strong earthquakes having the high energy frequency range of 1.0 Hz to 10Hz. One of the seismic isolation system commonly used is a high damping laminated rubber bearing(HLRB). Since HLRB has a comparably large damping, the accelerations in superstructure are remarkably reduced in horizontal direction. However the vertical stiffness of HLRB to transmit vertical load is relatively larger than horizontal one, the seismic responses in vertical direction are likely to be amplified. Thus vertical behavior of HLRB on seismic responses of superstructure should be evaluated.

In this paper, time history analyses for a typical PWR superstructure with a HLRB isolation system were performed to understand the effects of the seismic responses in superstructures and the results were compared to fixed base model. The reduction of vertical isolator stiffness is also suggested to decrease the vertical acceleration responses.

2. Structural Model

The model used in the analysis is shown in Fig.1. The isolated system considered in this paper consists of the isolator, base mat and the superstructure (containment vessel part and internal structure part). The computer program used in analysis is ABAQUS version 5.4[4]. The 2-D beam element (type=B21) and mass element (type=MASS, type=ROTARYI) are used for the superstructure, and spring element (type=JOINTC) for the isolator.

In the model, the nodes from 1 to 10 represent the containment vessel part and the nodes from 11 to 17 represent internal structure part. The nodes 18, 7 and 11 represent the base mat, the polar crane support and the horizontal reactor vessel support respectively. The total weight of the superstructure is about 68,000 kg. The structural damping of the superstructure is assumed to be viscous damping with 5% damping ratio for all modes. It is converted into Rayleigh damping for the mathematical model.

Fig.2 shows the shear cycle test results of the isolator, which is scaled down 1/8 size. In modelling of the isolator which has severe hardening characteristics in large strain region, a non-linear spring model with an equivalent viscous damping should be applied. However, the shear deformation is smaller than 150% shear strain, we can use an equivalent linear spring model for horizontal direction as follows :

$$Kh = 0.6887 \times 10^6 \ kg_f/cm.$$

The Kh is determined by an equivalent stiffness that is resonated at 0.5Hz in horizontal direction. The vertical stiffness of isolator is designed to resonance at 22 Hz as follows:

$$Kv = 1208.0 \times 10^6 \ kg_f/cm.$$

The vertical stiffness is assumed to be in compression state because it always resists total structure weight. The viscous dampings of the isolator are 12% for horizontal and 5% for vertical directions respectively.

3. Dynamic Characteristics of Superstructure

In horizontal direction, the fundamental natural frequencies of the containment vessel and internal structures for fixed base[4] are 5.39 Hz and 15.73 Hz respectively, and for base isolated system are 5.94 Hz and 16.17 Hz respectively. The first frequency of the isolated system is 0.5 Hz. Fig.3 shows the first five modes of the base isolated model in horizontal direction.

In vertical direction, the fundamental natural frequencies of the containment vessel and internal structures for fixed base[5] are 12.15 Hz and 26.8 Hz respectively, and for base isolated system are 11.42 Hz and 27.95 Hz respectively. The vertical frequency of the isolated system is 22.1 Hz. Table 1 shows the several frequencies of the models.

4. Effects of Isolator on Seismic Structural Responses

The isolated system is assumed to be subjected to horizontal and vertical 1940 El Centro earthquakes as shown in Fig. 4. The effects of the isolator on the superstructure responses are investigated by using the numerical simulations.

In Fig.5 the horizontal zero period acceleration at the superstructure for the isolated system, of which represents rigid body motion, are remarkably reduced to 0.125g at reactor support and 0.13g at polar crane support when it is subjected to horizontal El Centro earthquake(N-S). It is noteworthy that the acceleration at the crane support for the fixed base system is 0.91g and that at reactor support is 0.33g respectively. The acceleration responses at the polar crane support of the containment vessel are slightly amplified around 6 Hz, and are also larger than those of the reactor vessel support of the internal structure because the flexible structure can be excited larger than the stiff structure when subjected to an earthquake having lower frequency content excitation.

Fig.6 shows the results of numerical simulation of the relative displacement at the polar crane support of the fixed base and base isolated superstructures. From Fig.6, one can see that the relative displacement of the base isolated system is much larger than the fixed base model.

Fig.7 shows the results of the numerically simulated effects of vertical stiffness when it is subjected to vertical El Centro earthquake. The vertical zero period accelerations at the superstructure for the isolated system are increased to 0.44g at reactor support and 0.99g at polar crane support while those for the fixed base system are 0.26g at reactor support and 0.80g at polar crane support respectively. The isolator stiffness in vertical direction enlarges the maximum peak values of the superstructural vertical accelerations.

In order to reduce the vertical response of the superstructure, the vertical stiffness proposed is the 1/15 of the original one, then the fundamental frequency in vertical direction is reduced to be 5.21 Hz from 11.42 Hz. The vertical responses with this proposed stiffness are shown in Fig.8. The vertical zero period acceleration, 0.42g, at reactor support of superstructure is slightly decreased while the one at polar crane support is reduced to 0.48g.

5. Conclusions

The acceleration responses in base isolated PWR superstructure subjected to 1940 El Centro earthquakes are much smaller than those in fixed base superstructure in horizontal direction. But the vertical acceleration responses are larger than those in fixed base superstructure. Vertical seismic isolation with the reduced vertical stiffness of isolator is more effective in reducing the vertical seismic responses. In the base isolated system, the seismic acceleration responses at flexible structure are much more reduced than those at stiff structure. The horizontal relative displacement of the isolated structure is much larger than the fixed base structure.

The further research to implement the vertical isolation design for the reduction of vertical seismic responses is needed.

References

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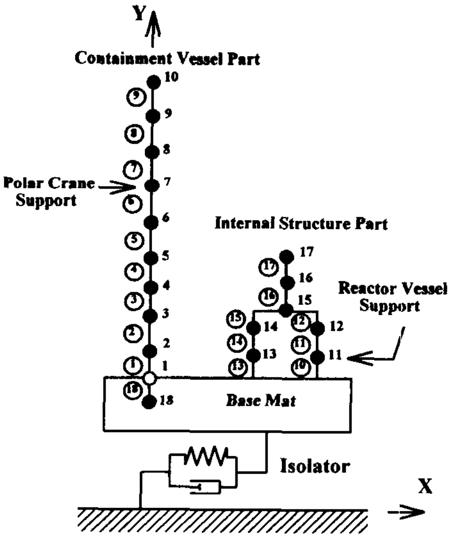

Fig. 1. Model of PWR Reference Plant

Table 1. Isolated Frequencies of PWR Reference Plant

	Horizontal		Vertical	
Mode No.	Frequency (Hz)	Parti.Factor	Frequency (Hz)	Parti.Factor
1	0.5	1.01060	11.42	1.7778
2	5.94	-0.01120	22.0	-1.2286
3	16.17	-0.00013	27.95	0.3818
4	17.77	-0.00120	45.03	-0.3347
5	23.76	-0.00026	53.44	0.3411
6	30.92	0.00020	62.04	-0.1561

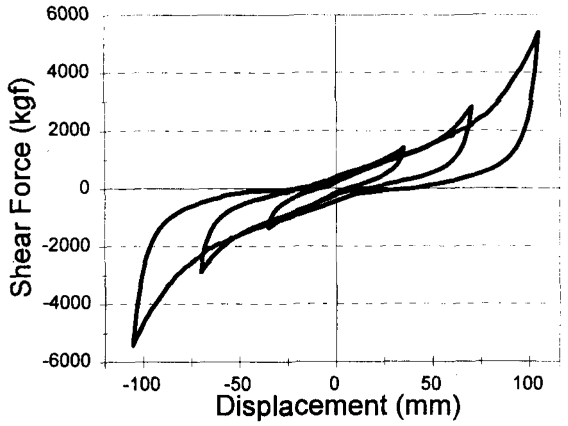

Fig. 2. Hysteretic Curve of 1/8 Scale HLRB

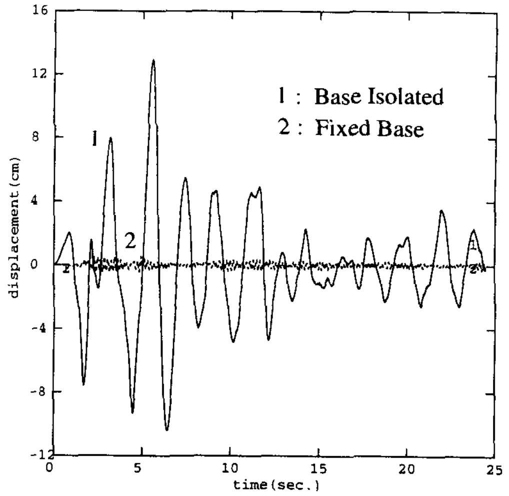

Fig. 6. Relative Displacements at Polar Crane

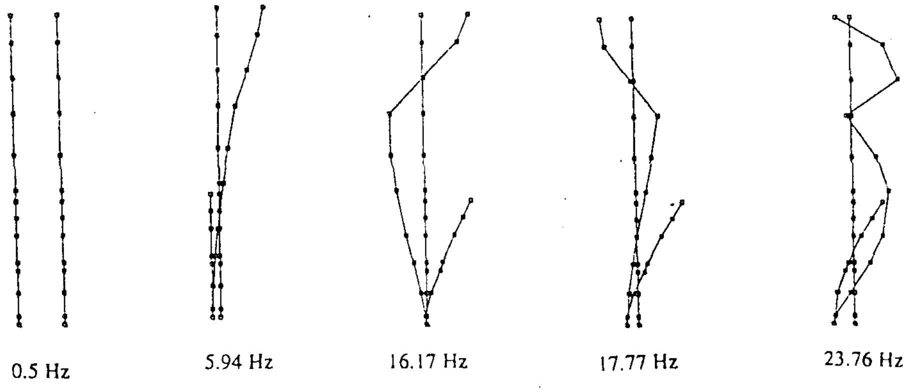

Fig. 3. Mode Shapes of Base Isolated Superstructure

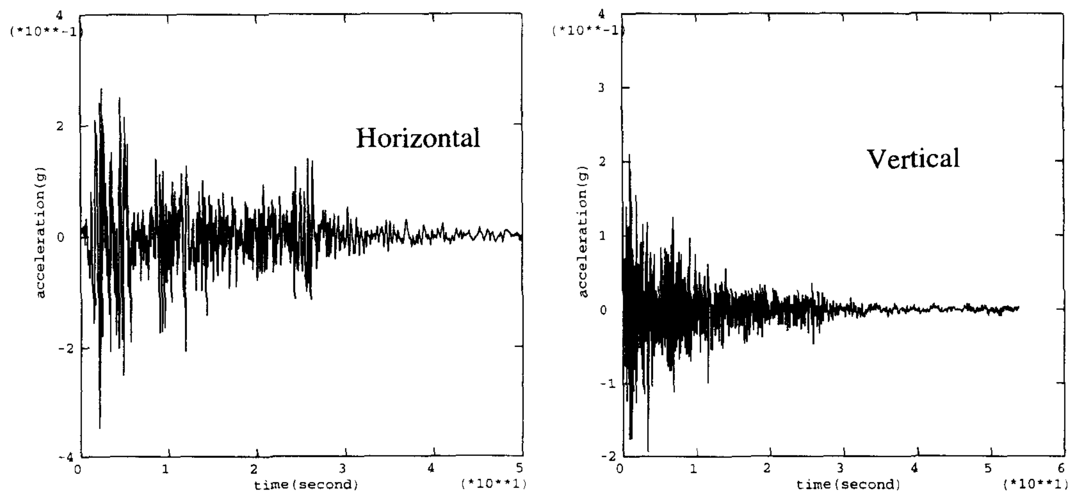

Fig. 4. Aceeralation Time History Data of 1940 El Centro Earthquake

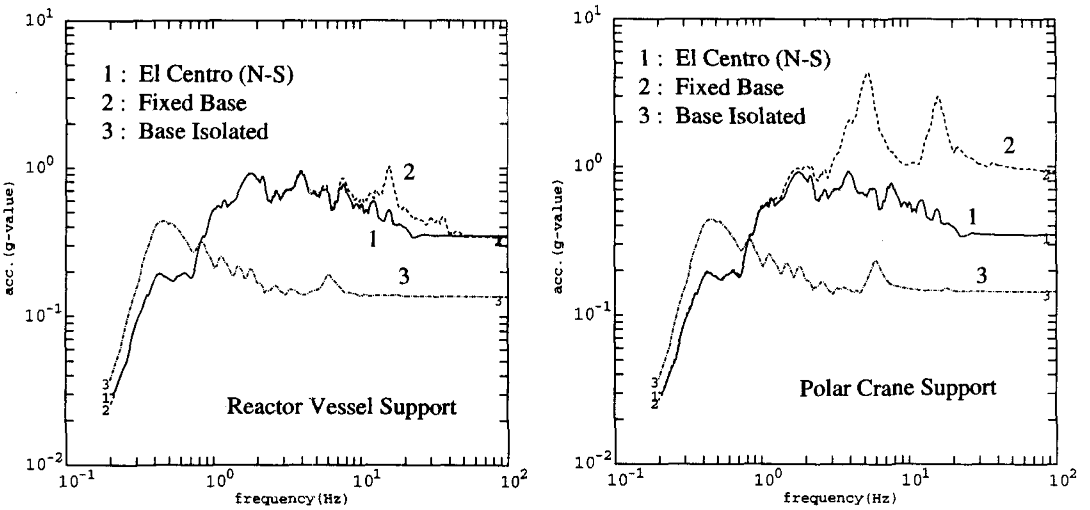

Fig. 5. Horizontal Acceleration Response Spectra of Superstructure

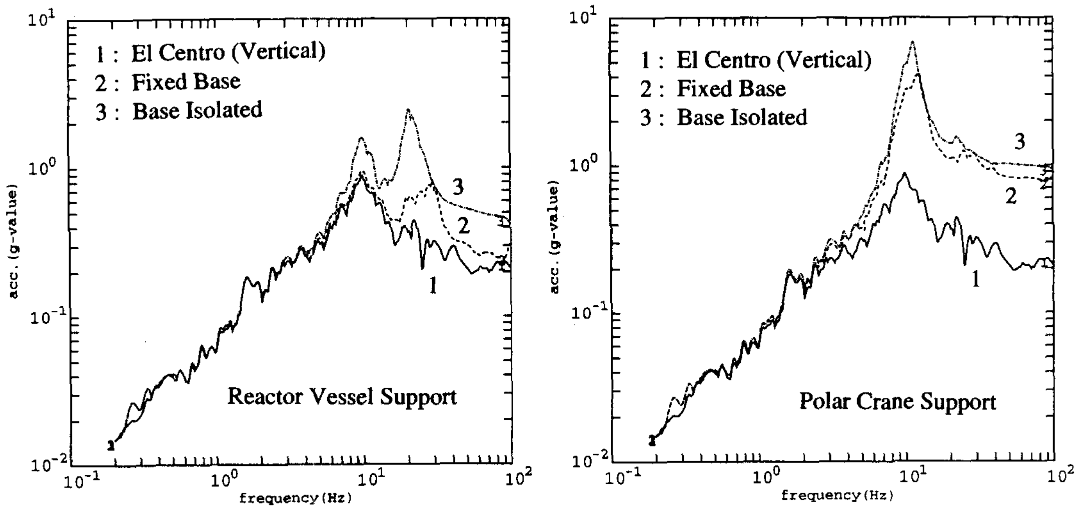

Fig. 7. Vertical Acceleration Response Spectra of Superstructure

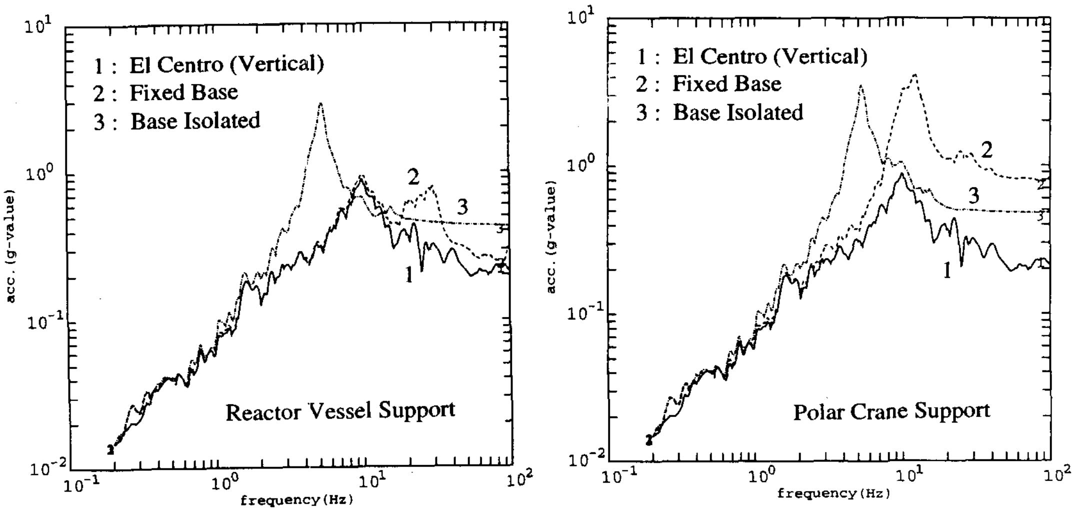

Fig. 8. Vertical Acceleration Response Spectra of Superstructure with Vertical Soft Stiffness