Structural Damping Effects in Seismic Responses of PGSFR Reactor Structure

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1. Introduction

PGSFR (Prototype Gen-IV Sodium Cooled Fast Reactor) has adopted a horizontal seismic isolation system.

The isolated system has wide range frequency spectrum from a low horizontal isolation frequency to several high structural vibration ones. Usually, the Rayleigh structural damping values are determined by taking into account of all the modes significantly contributing to the vibrations to get the adequate seismic responses.

At the frequency outside the range of these two bounding frequencies, the damping will be dramatically increased and the modal responses at the corresponding frequency range will be eliminated.

Several seismic time history analyses have been performed for an artificial time history (ATH) earthquake of 0.5g by changing the Rayleigh damping parameters, and the response results are evaluated.

2. Configuration of analysis model

The reactor building has a circular dome shape, it is located at the center area of the PGSFR auxiliary building, which is connected to the reactor building at the common basemat as shown in Fig.1. The reactor building includes a 1.5 m thick reactor support wall at the innermost side and a huge cylinder-dome containment at the outside. The reactor structure modeled with 3D shell elements and 3-D beams is supported on the reactor support wall. The analysis model is of 45,032 tons, including the reactor structure.

The vertical support load of one isolator is about 1,000 tons. The 45 isolators support the reactor building below the basemat excluding the auxiliary building.

3. Seismic response time history analysis

3.1 Modal analysis

The natural frequencies of the analysis model are calculated. In the modal results, the isolation frequency of 0.4 Hz does not appear since the primary horizontal stiffness (K1) of the isolator, which is about 100 times higher value than the secondary softening stiffness (K2), is used. The first and second frequencies in horizontal are 2.28 Hz and 4.70Hz, respectively. The secondary softening stiffness (K2) of the isolator will actively influence on the isolation response behavior for a strong seismic load over 0.5g. The first frequency in vertical direction is 9.08 Hz.

The natural frequencies of the reactor structure supported on the reactor building, and the seismic load paths are represented in Fig.2.

3.2 Structural damping modeling

Even though Rayleigh damping is very convenient for modeling, the variation of damping ratio with frequency is not available. The high and low frequency vibrations that are outside the frequency range of interest will be damped out in the seismic response analysis.

The mass proportional damping(α) introduces externally supported dampers, which do not exist for a fixed structure. The stiffness proportional damping(β) increases the damping dramatically at a higher order of vibration modes.

The seismic response analyses were performed for the four cases of the different damping parameter sets in Table 1 to evaluate the structural damping effects in seismic responses of PGSFR reactor structure.

Table 1 Modeling of damping parameters

Case No.	Rayleigh structural damping parameters ($\times 10^{-3}$)						Damping ratio
	RV & internal		Reactor building		Isolator		
	α	β	α	β	α	β	
1	309.47	0.475	309.47	0.475	309.47	0.475	- 5% at 0.5Hz, 33Hz for all model
2	0	0.475	0	0.475	0	0.475	- 5% at 33Hz for all model
3	1736.4	1.19	0	1.19	0	0	- 5% at 3Hz, 12Hz for RV -5% at 12 for building
4	2345.7	1.188	47.18	1.585	0	0	- 5% at 5Hz & 10Hz - 1% at 0.5Hz, 7% at 14Hz for building

The model of Case 1 is that the damping at the two specific frequencies is identical for the whole model. The structural damping is as follows;

- $\alpha = 0.30947$, - $\beta = 0.000475$.

It means that 5% structural damping ratio is applied for the two frequencies at 0.5 Hz and 33 Hz.

The model of Case 2 is that only the stiffness proportional damping of 5% at 33 Hz is adopted for the whole model. There is no mass-proportional damping effect. Regarding to the Cases 1&2, a very low structural damping is applied for the reactor structure vibration modes from about 1 Hz to 12 Hz as shown in Fig.3.

The model of Case 3 is that 5% structural damping is set to the reactor structure in the range 3Hz to 12 Hz while the reactor building is set to 5% damping only at

12 Hz. In this case, the structural damping ratio is less than 1% at the isolation frequency of 0.4 Hz since there is no mass-proportional damping contribution in reactor building of heavy mass.

The model of Case 4 is that the structural damping coefficient [α, β] of the analysis model is set so that the structural damping ratio is less than 5% for the frequency range between 5 Hz and 10 Hz in reactor structure, and mass-proportional damping of reactor building is set 1% at the isolation frequency.

3.3 Seismic responses to the beyond seismic load

The seismic response analysis results for four cases were evaluated at selected points. The acceleration responses at the reactor support and at bottom of reactor vessel for 0.5g seismic load were obtained by allocating the different structural damping for each sub-structure model, such as reactor structure, reactor building, and isolators.

The horizontal seismic accelerations transmitted to reactor structure are not amplified, and which are reduced by a half through the isolator hysteresis damping. In Case1&2, the maximum vertical accelerations are amplified by 1.135g and 1.649g respectively at RV bottom, which are higher than Case 3&4 because the very low structural damping is applied between 3 Hz and 10 Hz of the dominant frequency range of the reactor structure. In Case3&4, the maximum accelerations at RV bottom are less than the limiting value of 1g, which prevents any fuel lifting possibility condition.

The isolator maximum deformations are calculated by 386 mm, 502 mm, 490 mm, and 467 mm for 4 Cases in Table 1. The LRB deformation was strongly related with the structural damping values at isolation frequency of 0.4 Hz. As for Case1 resulted LRB deformation of 386 mm, 7% structural damping is additionally contributing to the seismic isolation mode excluding the isolator hysteresis damping, while low structural damping values of about 1 % are applied to others.

As shown in Fig.4, the structural damping coefficients must be determined so that it does not become an over-damping value at the isolation frequency of an isolated structure system.

As for Case4, the maximum accelerations at reactor vessel and reactor support were decreased as optimal damping allocation to each sub-structure.

With respect to the reactor vessel support position, the relative displacements of Case4 at the bottoms of the reactor vessel and the internal redan were respectively recorded as about 10 mm and 20 mm as shown in Figs.5&6.

The seismic displacement responses for 0.5g seismic load of an outside isolator of Case4 were represented in Fig.7 and Fig.8. The maximum seismic displacement response of the isolator was calculated by 467 mm (311% shear deformation), which is acceptable value because it is within 450% shear deformation limit of the isolator. The vertical displacement hysteresis of an outside isolator was in the range of 0.1 mm to 2.1 mm in compression state for the ATH seismic load of 0.5g. The vertical resisting forces of the isolator were represented in Fig.9.

4. Conclusions

In the analysis, the reasonable seismic responses for the vertical acceleration at reactor support were achieved with the acceptable seismic deformation of isolator for the beyond ATH seismic load of 0.5g.

The structural damping parameters that affect the seismic responses of PGSFR reactor structure were identified. The seismic response accelerations in the reactor structure were reduced by the structural damping optimization.

The seismic responses for the Case4 damping condition were acceptable in perspective of the acceleration response and isolator deformation for a high level seismic load of 0.5g.

ACKNOWLEDGEMENT

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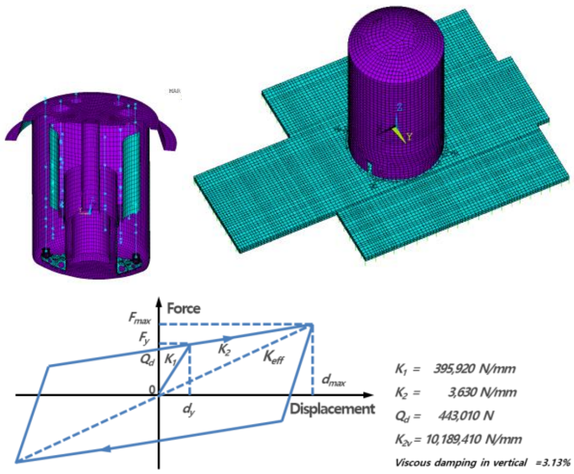

Figure 1 Reactor structure, basemat and lead rubber bearing (LRB) models of the PGSFR

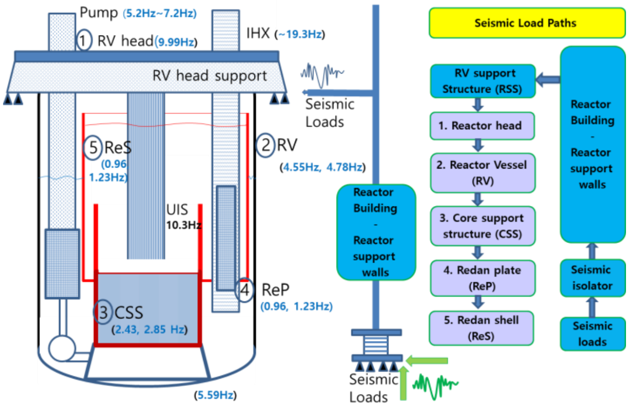

Figure 2 Natural frequencies of reactor structure and seismic load paths

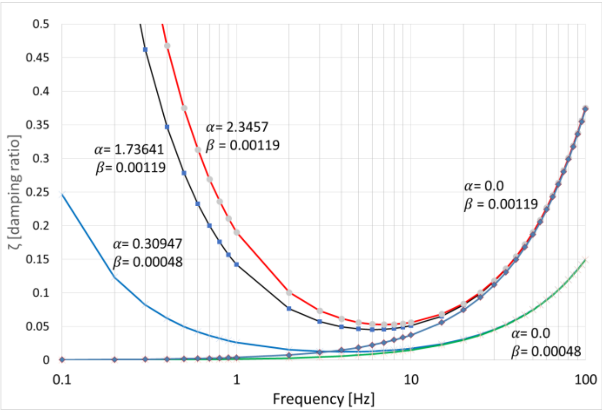

Figure 3 Rayleigh structural damping ratios for two coefficient parameter sets

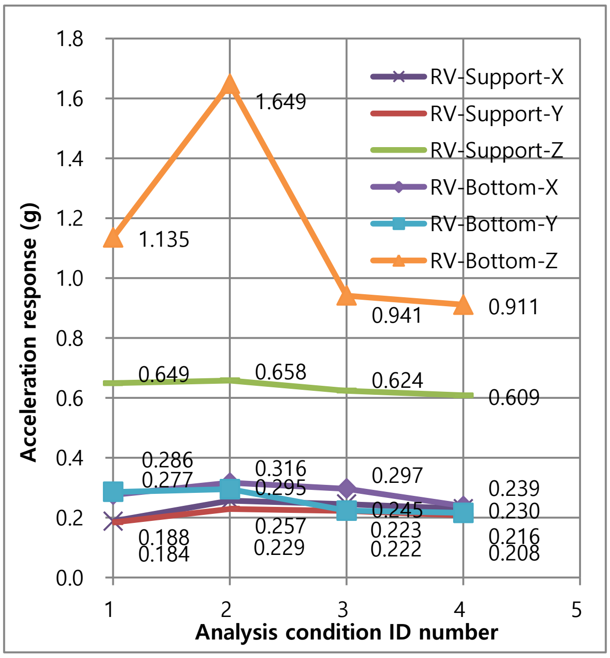

Figure 4 Seismic acceleration responses at the reactor vessel bottom and the vessel support for 4 Cases in Table 1

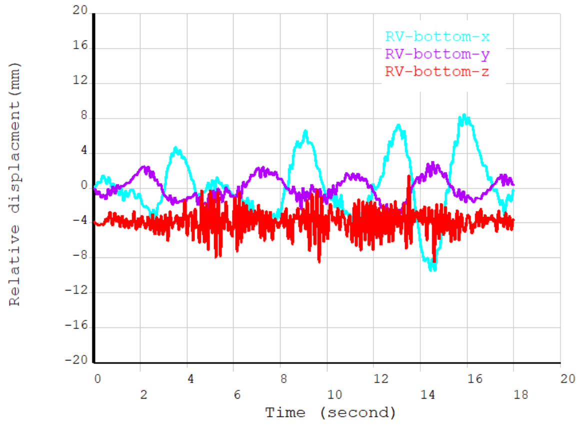

Figure 5 Seismic displacement responses at bottom of reactor vessel (0.5g) – Case4

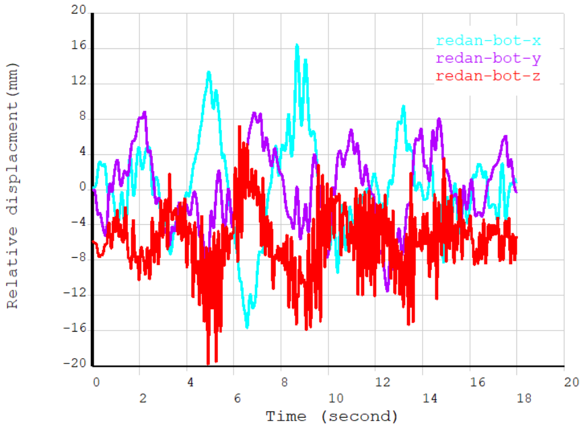

Figure 6 Seismic displacement responses at bottom of redan (0.5g) – Case4

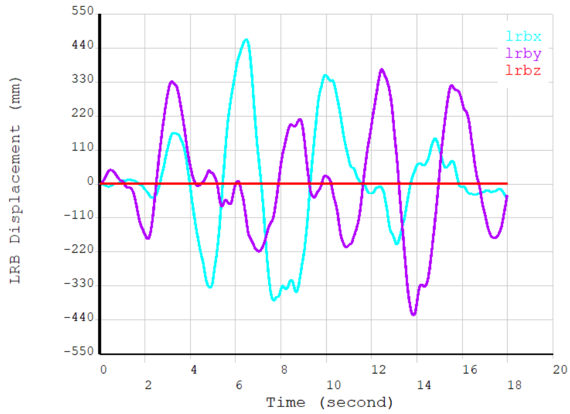

Figure 7 Horizontal seismic displacement responses of an outside isolator (0.5g) – Case4

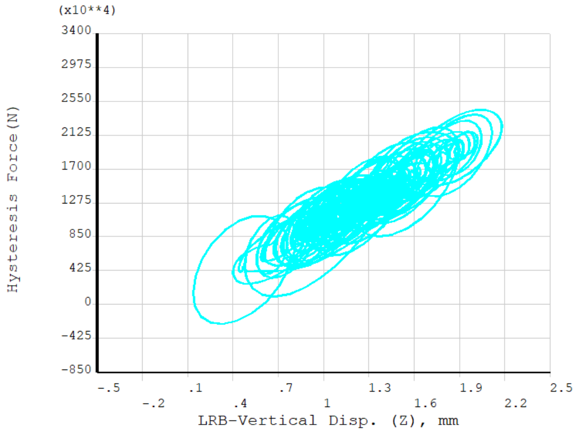

Figure 8 Seismic response of vertical deformation hysteresis of an outside isolator (0.5g) – Case4

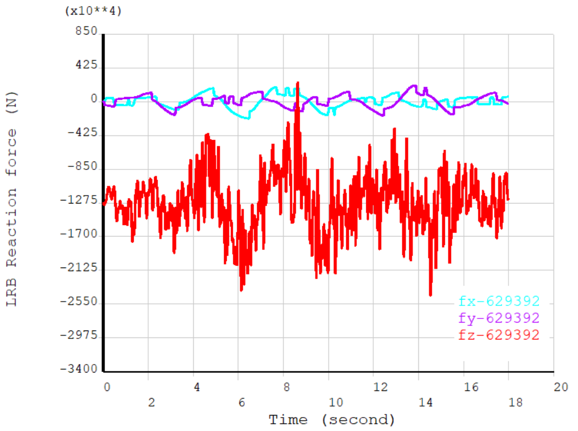

Figure 9 Vertical seismic reaction forces of an outside isolator (0.5g) – Case4