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Evaluation of Floor Response Spectrum considering Ductility of Structure

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1. Introduction

When the seismic fragility is performed, the floor response spectrum (FRS) is the important variable because the floor acceleration response is the input of equipment located in floor level. The FRS is directly influenced by the behavior of structure under the seismic load. If the structure is nonlinear range, the energy dissipation will be occurred by the damage of structure and the maximum force will be reduced. In Zion method [1], the inelastic energy abortion factor has been used to consider the nonlinearity of structure. This factor was used for the seismic fragility of structure. For the seismic fragility of equipment, the uncertainty of this factor was used differently according to the story level. But this method is not warranted under the strong earthquake leads to the structural damage. Therefore it is needed to evaluate the FRS considering the nonlinear behavior of structure and to assessment the conservatism related to nonlinear behavior of structure in FRS.

In this study, the nonlinear analysis was performed for the conservatism of FRS under the damage of structure. The conservatism of FRS by the nonlinear analysis was compared by that proposed by the Zion method.

2. A factor influencing floor response under the nonlinear behavior of structure

From the results of Robert et. al. [2], it was reported that the input spectrum, hysteretic model of structure elements, location of equipment and structure damping have effect on the response of equipment under nonlinear behavior of structure.

The FRS can be changed by the spectrum shape of input motions. The hysteresis model for structural elements and the damping for the structure are closely related with the energy absorption of structure. The pinching effect was considered for identifying FRS by the hysteresis model.

Because it is inefficient to perform the nonlinear analysis for many equipment of nuclear power plants (NPPs) the seismic fragility for the equipment has been conducted using the response factor related to the nonlinear behavior of structure. In Zion method, this factor was equally applied for the all structure of NPPs. And the logarithmic standard deviation of this factor was applied considering the story level.

3. Input ground motion

As an input motion, nine real earthquake ground motion and one artificial seismic motion developed based on US NRC Reg. guide 1.60 [3] were selected to perform nonlinear analysis as shown in Fig. 1.

Characteristics of these ground motion records were selected considering the frequency content, the local magnitude, and the strong duration.

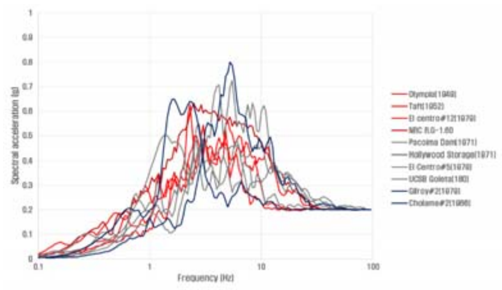


Fig. 1. Input spectral acceleration

4. Analytical model

For the structure analysis, the structure was modeled by single degree of freedom (SDOF). It was assumed that the height of structure was 518cm. The fundamental frequency of the structure was 4.0Hz considering that the fundamental frequency of containment building was about 4.0Hz. The nodal mass and stiffness were 360kN-sec^2/cm and 228465kN/cm, respectively.

The fixed boundary condition was assumed. The shear wall of containment building can behave nonlinear under the strong earthquake. In this study, the hysteretic model of OpenSEES (Open System for Earthquake Engineering Simulation) [4] was used for considering the damage of shear wall as shown in figure 2.

The FRS was calculated at the top of structure by performing the linear/nonlinear analysis.

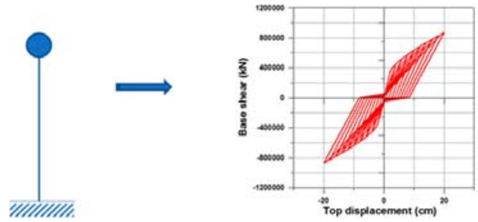


Fig. 2. Analytical model and hysteresis curve

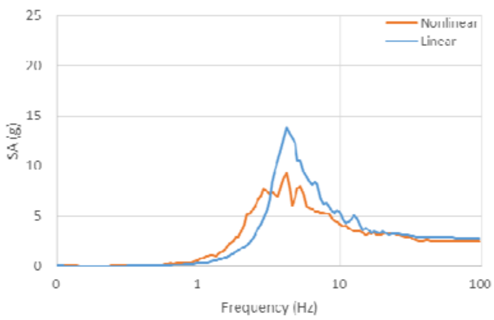
5. Floor response spectrum by nonlinear analysis

5.1 FRS by inelastic structural behavior

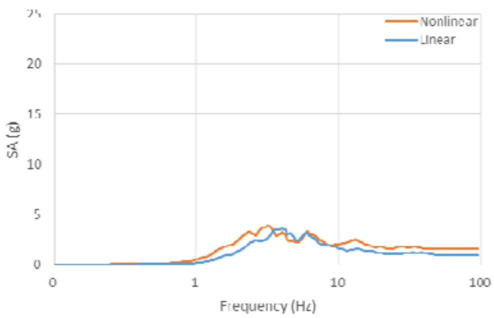
The FRS was related to the nonlinear behavior of structure. In this study, the FRS by linear/nonlinear analysis was compared to evaluate the conservatism of FRS due to the nonlinear response.

For identifying the increase/decrease of FRS by the nonlinear behavior of structure, the peak ground acceleration (PGA) was increased until the displacement of top exceeded the yield displacement.

The figure 3 showed the FRS by analysis method. The FRS reductions are seen at the fundamental structure frequency for nonlinear response. The FRS increases between 0Hz ~ 3Hz are seen by nonlinear analysis. It was concluded that this result was caused by the stiffness softening of structure under the strong earthquake. Although it was presented that the FRS for the Cholame earthquake with low frequency content was increased in the high frequency range. At high frequencies (above 4 Hz), it was showed that the inelastic spectral response is generally lower than the elastic spectral response.



(a) FRS by Taft earthquake



(b) FRS by Cholame earthquake

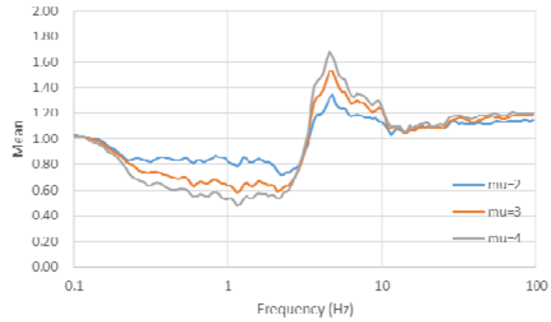
Fig. 3. FRS by nonlinear response of structure

5.2 FRSR by ductility of structure

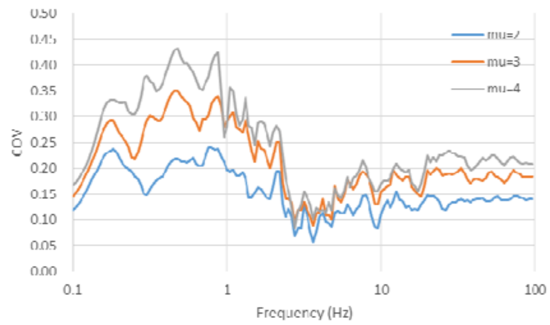
In this study, the ratio of nonlinear response to linear response was presented by the floor response spectrum ratio (FRSR) for evaluating the conservatism of floor acceleration response due to the nonlinear behavior of structure. The FRSR was presented by ductility of structure as shown the figure 4 because the ductility has been used as the capacity index for the nonlinear structure. If the FRSR was the unity, it represented that the response by the nonlinear and linear analysis was equal. If the FRSR was above the unity, it represented that the FRS decrease was occurred by nonlinear behavior of structure.

From the figure 4, it was showed that the FRSR by the 10 earthquakes was different by frequency. When the ductility was 2, the mean of FRSR was 0.5~1.7 and the coefficient of variation (COV) of FRSR was 0.05~024. The peak value of the mean of FRSR was showed at 5.2Hz. When the frequency was lower than 3 Hz, the mean of FRSR was below unity because of the frequency shifting downward.

The median and COV was divided by frequency of equipment considering that the equipment of NPPs have the various frequency. In this study, the group of equipment was divided by the frequency as shown in table 1. The first group was 0~100Hz equipment including all equipment of NPPs. The second group was 4~10Hz equipment such as the Safety injection tank, pressurizer and reactor vessel. The structure and the equipment of second group have a similar frequency. The final group was the equipment of 10~100Hz such as the auxiliary equipment.



(a) Mean



(b) COV

Fig. 4. FRSR by ductility

Table 1. Category of equipment by frequency

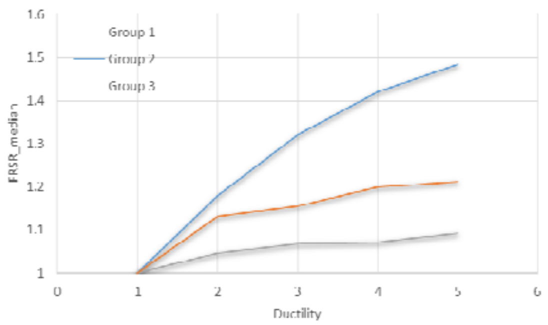
Group	Frequency (Hz)	Equipment
1	0~100	All equipment
2	4~10	Pressurizer Reactor vessel
3	10~100	RCP Regenerative heat exchanger

Figure 5 showed the median and β_c of FRSR by the group of equipment. The median and β_c were increased with the ductility of structure.

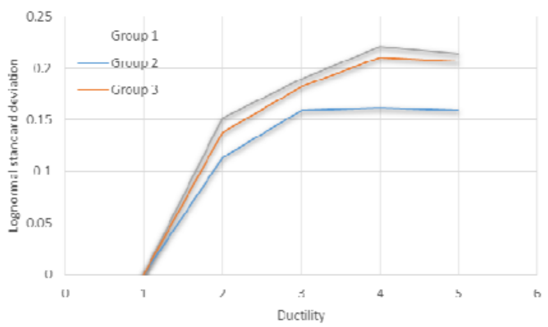
Among the group of equipment, the median of first group was the lowest because of the frequency shifting downward. It was represented that the median of second group was the highest. Therefore the reduction of floor acceleration response will occur when the frequency of equipment is similar or higher than that of structure.

The median and β_c of FRSR can be compared with response factor and logarithmic standard deviation for the inelastic structure response of the Zion method. In Zion method, the median of 1.0 and the logarithmic standard deviation of 0.2 were used.

The Zion method using the linear analysis is a simplified method for evaluating the seismic fragility for structure and equipment of NPPs. So this method has a conservatism of capacity and response for structure/equipment. From a comparison the factor by Zion method and this study results, it was showed that the inelastic structure response factor by Zion method was lower than the median of FRSR by this study. Therefore it was found that the inelastic structure response factor for equipment using the Zion method was underestimated.



(a) Median



(b) COV

Fig. 5. The median and β_c of FRSR by group of equipment

6. Discussion

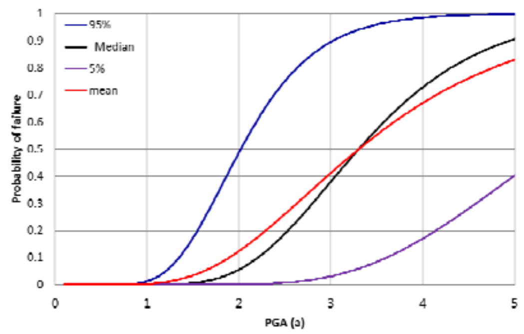
From the analysis results, it was concluded that the median and β_c for FRSR was increased with the ductility of structure. The FRSR of this study was related to the inelastic structure response factor of seismic fragility.

The seismic fragility analysis was performed for evaluating the seismic capacity of equipment considering the inelastic structure response factor.

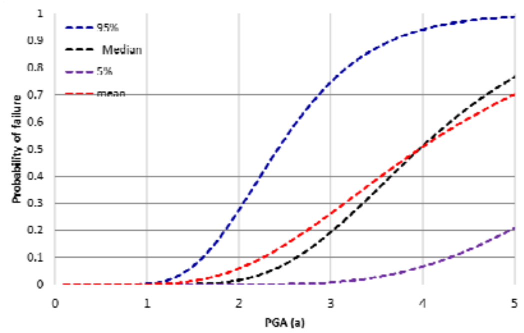
It was assumed that the ductility of structure was 4. The regenerative heat exchanger (RHE) corresponding the group 3 was selected. The median and β_c for the inelastic structure response factor considering the ductility was 1.2 and 0.21, respectively. While the median and β_c for the inelastic structure response factor by Zion method was 1.0 and 0.2, respectively.

Figure 6 showed the seismic fragility curve using the current factor of Zion method and the modified factor of this study result. The seismic capacity of equipment can be shown in table 2. The median capacity and the high confidential of low probability of failure (HCLPF) capacity was increased about 20% with the inelastic structure response factor.

The inelastic structure response factor should be modified considering the frequency of equipment and the ductility of structure.



(a) Current factor



(b) Modified factor

Fig. 6. Seismic fragility curve of RHE

Table. 2. Seismic fragility result of RHE by inelastic structure response factor

Variables	Current factor	Modified factor
A_m (g)	3.30	3.97
β_r	0.31	0.32
β_u	0.30	0.30
HCLPF(g)	1.20	1.43

7. Conclusion

The nonlinear behavior of structure is occurred by the beyond design earthquake. If the structural damage was occurred by earthquake load, it is difficult to expect the floor response of structure using the response factor.

In this study, the characteristic of FRS was analyzed by the ductility of structure. The conservatism of floor acceleration response for the equipment was evaluated by performing the nonlinear analysis.

From the nonlinear analysis results, it was showed that the median and β_c of FRSR was increased with the ductility of structure and the response of equipment had the resonance effect between the frequency of equipment and structure.

The seismic capacity of equipment by the Zion method can be different from the real seismic capacity of equipment because the inelastic structure response factor has nothing to do with the ductility of structure. Therefore the median and COV for FRSR should be defined considering the ductility of structure and the frequency of equipment for more exactly evaluating the seismic capacity of equipment.

Acknowledgement

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REFERENCES

[1] TR-103959, Methodology for Developing Seismic Fragility, EPRI, 1994.

[2] Robert T. Sewell, C. Allin Cornell, Gabriel R. Toro, and Robin K. McGuire, A Study of Factors Influencing Floor Response Spectra in Nonlinear Multi-Degree-of-Freedom Structures, Department of Civil and Environmental Engineering Stanford University, Report No. 82, November 1986.

[3] Regulatory Guide 1.60, Design Response Spectra for Seismic Design of Nuclear Power Plants, U.S Nuclear Regulatory Commission.

[4] Mazzoni, S., McKenna, F., and Fenves, G., OpenSees Command Language Manual, Pacific Earthquake Engineering Research (PEER) center, 2005.