13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 2872

EVALUATION OF SEISMIC CAPACITIES OF KOREAN NUCLEAR POWER PLANT STRUCTURES BY SEISMIC FRAGILITY ANALYSIS

S.G. CHO[1], Y.H. JOE[2] and G.S. PANG[3]

SUMMARY

Seismic fragility analysis (SFA) has been utilized as a tool to evaluate the actual seismic capacity of structures and equipments in nuclear power plant (NPP) industry. This paper presents a brief discussion about the Korean practical method of SFA, focusing on the basic input variables. In order to obtain more reasonable SFA results, an improved definition of the response spectrum shape factor that is one of the important input variables is proposed. The new factor is expressed as a term of linear algebraic sum of modal responses reflecting different modal contribution of each mode to consider the multimode effect of structural response.

The efficiency of the new factor has been validated to use in practice through the case studies. For the purpose, the five representative NPP structures in Korea were selected as objective models. The seismic capacities of the structures obtained by considering single mode response were compared to those obtained by considering multimode response. The analysis results showed that the proposed factor can be more effectively applicable to multimode structures with composite modal damping.

INTRODUCTION

It has been increased to utilize the seismic probabilistic risk assessment (SPRA)[1] rather than deterministic approach for resolving seismic safety issues of critical industrial facilities by reflecting more reasonable information. In the field of the nuclear power plant (NPP) engineering in which the safety issue is more significant than other industrial fields, the SPRA is a regulatory requirement for construction and operation of the plant. The key elements of SPRA methodology are identified as seismic hazard analysis, seismic fragility analysis (SFA), plant system and accident analysis, and consequence evaluation [2]. The SFA is a step to evaluate the actual seismic capacity of structures. Thus, SFA is the most significant and essential phase especially for structural/mechanical engineers.

The SFA methodology that has been developed in some high seismicity countries has been described in a number of papers and reports [1], [2], [3], [4]. The US Electric Power Research Institute (EPRI) presented

[1] Ph.D., Structural Vibration Engineering Lab., Univ. of Incheon, Incheon, Korea, sgcho@incheon.ac.kr
[2] Prof., Dept. of Civil Engineering and Environmental System Eng., Univ. of Incheon, Incheon, Korea
[3] Researcher, Korea Electric Power Research Institute, Daejeon, Korea

a practical guidance [5] for performing SFA for the NPP. For all operating plants in the US, the SFA has been conducted since 1992 [6]. On the contrary, it has not been long to apply the probabilistic concept to the seismic evaluation of major industrial facilities in Korea. A basic implementation procedure of SFA for NPP structures was first introduced in Korea in 1992 [7]. A few research works about the improved methodology to incorporate the local characteristics of Korea have been performed, recently [8], [9].

This paper discusses on a practical method that has been utilized in Korea, focusing on the basic input fragility variables. Especially, a new definition of the response spectrum shape factor as one of the most critical basic variables is introduced to consider the multimode response of structure. The new factor is expressed as a term of linear algebraic sum of modal responses considering different modal contribution of each mode. The effects of the multimode response are evaluated through the comparative studies for several representative NPP structures in Korea. From the evaluation of results, the applicability of the new factor is validated.

BASIC METHODOLOGY FOR SEISMIC FRAGILITY ANALYSIS

SFA is performed to evaluate the actual seismic capacity of structure considering the total variability in seismic input, structure response, and material capacity variables. The variability is categorized as two types. The part of variability that is reducible by more detailed studies and experiments is defined to be uncertainty. The randomness that cannot be practically reduced is the other variability resulted from the nature of earthquake motion.

The seismic fragility of a structure is defined as the conditional probability of its failure for a given value of the seismic response [2],[3]. The SFA result is expressed by a set of cumulative distribution curves of probability of failures for a given ground level at any confidence level. Using the lognormal distribution as a fragility model, the seismic fragility is calculated by equation (1)[3].

$$P_f = \Phi\left(\frac{\ln\left(\frac{a}{A_m}\right) + \beta_U \Phi^{-1}(Q)}{\beta_R} \right) \tag{1}$$

Where, P_f : probability of failure

$\Phi(.)$: cumulative distribution function of normal distribution

Q : non-exceedence probability level (5%, 50%, or 95% confidence level in usual)

$\Phi^{-1}(.)$: inverse cumulative distribution function of normal distribution

A_m : median seismic capacity that is a ground motion level (usually, peak ground acceleration)

a : a given ground motion level (usually, peak ground acceleration)

β_R : logarithmic standard deviations for randomness of seismic capacity

β_U : logarithmic standard deviations for uncertainty of seismic capacity

The 5% probability of failure point on the 95% confidence curve is defined as the high confidence of low probability of failure (HCLPF) value, which is used as an index to measure the seismic capacity of the structure [3]. The HCLPF is calculated by equation (2).

$$HCLPF = A_m \cdot \exp[-1.645(\beta_R + \beta_U)] \tag{2}$$

Several basic input variables are considered in SFA, which are separated into response variables and capacity variables. The response variable is to account for the conservatism of seismic response included in design which may be resulted from the variability of design ground motion, damping values, and caused by the techniques of modeling, mode combination, earthquake component combination, soil-structure interaction analysis, and so on. The strength and the inelastic energy absorption capacity of structural members are considered as capacity variables to reflect the actual resistance of structures under the design earthquake.

For the convenience of practical application, the seismic capacity is expressed by the reference capacity value times to a scale factor (or response factor) that is a measure of conservatism included in seismic design and a ratio of design response to actual response. Thus, the total seismic capacity of structure is determined by equation (3).

$$A = \left(\prod_i F_{Ci} \cdot F_{Ri} \right) \cdot a_{ref} \tag{3}$$

Where, A : seismic capacity of structure

F_{Ci} : i-th scale factor for seismic capacity variable

F_{Ri} : i-th scale factor for seismic response variable

a_{ref} : reference ground acceleration (usually, design earthquake level)

Most of the scale factors of the Korean method are calculated by using the same equation as EPRI's[5]. However, for the response spectrum shape factor, the effects of multimode response is additionally considered to reflect more reasonable structural responses, while EPRI's method [5] use only the fundamental modal response. SFA introduces the response spectrum shape factor to account for the difference between the actual response spectrum and the reference response spectrum used in the design. Existing response spectrum shape factor is defined as the following equation

$$F_{SS} = \frac{S_A(\omega_n, \xi_n)_{design}}{S_A(\omega_n, \xi_n)_{actual}} \tag{4}$$

Where, $S_A(\omega_n, \xi_n)_{design}$: spectral acceleration of design response spectra for the n-th mode

$S_A(\omega_n, \xi_n)_{actual}$: spectral acceleration of actual response spectra for the n-th mode

The response spectrum shape factor reflecting the multimode effects can be newly expressed by equation (5) using the modal contribution factor for base shear which represents modal contributions to the total seismic response of the structure [8].

$$F_{SS} = \frac{\sum_{i=1}^{N} \gamma_n S_A(\omega_n, \xi_n)_{design}}{\sum_{i=1}^{N} \gamma_n S_A(\omega_n, \xi_n)_{actual}} = \frac{A_d}{A_a} \tag{5}$$

Where, γ_n : the *n*-th modal contribution factor

ω_n : the *n*-th modal frequency

ξ_n : the *n*-th modal damping

N : number of the total modes

A_d : design acceleration capacity (deterministic value)

A_a : actual acceleration capacity (random variable)

When a variable is expressed as lognormal distribution, the mean and standard deviation for the variable is obtained by equation (6) and (7) [5].

$$\mu_X = x_m \cdot \exp\left(\frac{1}{2}\beta_X^2\right) \tag{6}$$

$$\sigma_X = \mu_X \cdot \sqrt{\exp\left(\beta_X^2\right) - 1} \tag{7}$$

Where, μ_X, σ_X : mean and standard deviation of random variable, X

x_m, β_X : median and logarithmic standard deviation of random variable, X

In addition, if the underlying variables, X_i's are statically independent random variables and they are functionally related to the response variable, Y as equation (8), then its mean, μ_Y and standard deviation, σ_Y are obtained by equation (9) and (10).

$$Y = a_1 X_1 + a_2 X_2 + \cdots + a_n X_n \tag{8}$$

Where, a_i : constant

X_i : underlying variable

Y : response variable

$$\mu_Y = \sum_{i=1}^{n} a_i \mu_{X_i} \tag{9}$$

$$\sigma_Y = \sqrt{\sum_{i=1}^{n} {a_i}^2 {\mu_{X_i}}^2} \tag{10}$$

The design acceleration, A_d is considered as the deterministic value in SFA. On the contrary, because the SFA considers the variability of the actual earthquake, A_a is a random variable. The mean and standard deviation of A_a can be obtained by applying the equation (9) and (10) to equation (5). The median and logarithmic standard deviation of A_a are determined by inverse of equation (6) and (7), respectively as equation (11) and (12).

$$x_m = \frac{\mu_X}{\sqrt{1+\left(\frac{\sigma_X}{\mu_X}\right)^2}} \tag{11}$$

$$\beta_X = \sqrt{\ln\left[1+\left(\frac{\sigma_X}{\mu_X}\right)^2\right]} \tag{12}$$

Finally, the median of F_{SS} is obtained by substitution of median of A_a and its logarithmic standard deviation equals to the logarithmic standard deviation of A_a.

COMPARATIVE EVALUATION OF SEISMIC FRAGILITY

Structural Models

Some case studies were carried out to demonstrate the effectiveness and validity of the improved definition of response spectrum shape factor. SFA's have been performed for the several structures selected from the Korean standard NPP, YGN3&4 [10]. They are a containment building, an auxiliary building, a component cooling water (CCW) building, a refueling water storage tank (RWST), and an essential service water intake (ESW) structure. The containment building that consists of a right cylindrical wall closed on top by a hemispherical dome is constructed of prestressed concrete by horizontal and vertical post-tensioned tendons. Other structures are all rectangular reinforced concrete structures of shearwall type.

Table 1. Structural Properties of the Selected Models

Structure	Dimension [a)] (meter)	Damping [b)]	
		1/2 Yield Level	Yield Level
Containment building	43.9(D)×66.8(H)	5%	7%
Auxiliary building	66.4(W) × 98.8(L) × 37.8(H)	7%	10%
CCWB	17.4(W) × 31.1(L) × 17.7(H)	7%	10%
RWST	11.3(W) × 31.7(L) × 12.6(H)	7%	10%
ESWB	14.3(W) × 14.1(L) × 11.3(H)	7%	7%

Notes. a) D: Diameter, W: Width, L: Length, and H: Height
b) Percentage of Critical Damping

The size and design damping values of the structures are shown in Table 1, and their modal properties are summarized in Table 2. The two different damping values according to the stress levels (1/2 yield level for the design earthquake and yield level for the actual earthquake) are considered in SFA.

Response Spectra of Input Motions

Design response spectrum of YGN3&4 is a site-independent response spectrum recommended by USNRC [11]. Because no actual response spectrum is available in Korea due to the lack of the real strong motion records, the mean and 84.1 percentile (mean+1σ) curves of the NUREG/CR-0098 response spectrum [12] are used as actual earthquake response spectra at the site. Figure 1 typically compares the response spectra for the containment building.

Table 2. Modal Properties of the Selected Models

Model / Mode	Containment		Aux. Bldg.		CCWB		RWST		ESWB	
	Freq. (Hz)	γ (%)	Freq. (Hz)	γ (%)	Freq. (Hz)	γ (%)	Freq. (Hz)	γ (%)	Freq. (Hz)	γ (%)
1st	4.6	71.7	2.02	6.8	14.33	85.0	0.23	4.7	5%	86.0
2nd	13.4	19.5	2.06	5.8	27.69	15.0	9.56	22.7	≥33.0	14.0
3rd	24.1	2.5	7.06	60.4	≥33.0		13.25	59.7		
4th	27.6	2.3	15.99	4.1			23.73	11.0		
5th	≥33.0	2.1	18.68	13.3			≥33.0	1.9		
6th			≥33.0	9.6						

Notes. γ: modal contribution factor

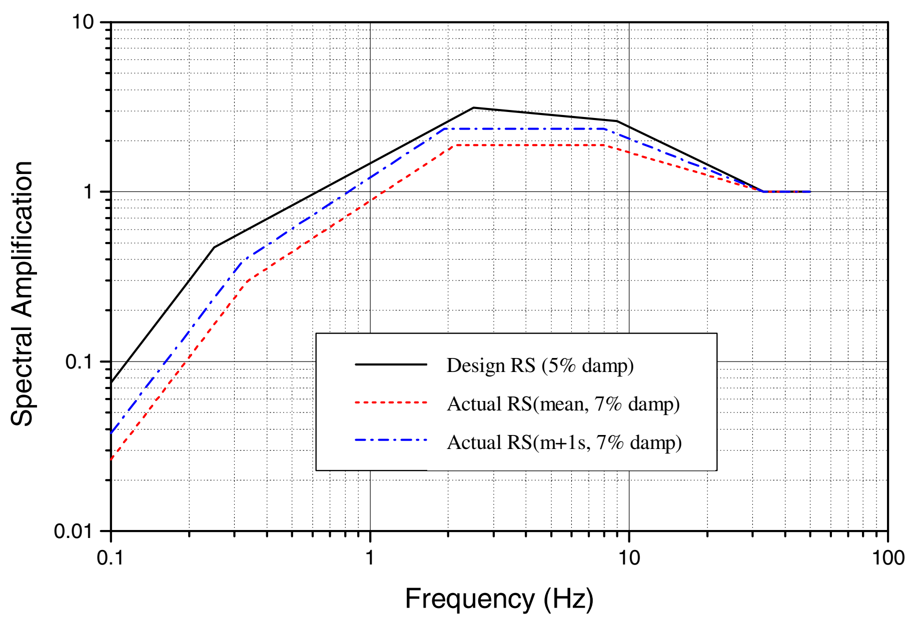

Figure 1. Comparison of Response Spectra

Comparison of SFA Results

Table 3 shows the median response spectrum shape factors and its logarithmic standard deviations. The median factor and its logarithmic standard deviation due to randomness were calculated by using the mean and mean+1 standard deviation curves of Newmark's spectra. This study used the typical ranges for the spectral shape uncertainty of the Newmark's spectra recommended by EPRI guidance [5].

Table 3. Comparison of Response Spectrum Shape Factors

	Single Mode Case			Multimode Case		
	Median Factor	β_R	β_U	Median Factor	β_R	β_U
Containment Bldg.	1.52	0.22	0.24	1.46	0.17	0.18
Aux. Bldg.	1.15	0.19	0.20	1.22	0.12	0.12
CCWB	1.26	0.11	0.13	1.24	0.10	0.11
RWST	1.29	0.12	0.14	1.24	0.09	0.09
ESWB	1.09	0.07	0.002	1.08	0.06	0.002

The fragilities of the objective structures using the existing and improved response spectrum shape factors are resulted and compared shown in Table 4. The existing method that considers only one dominant mode estimates the lower seismic capacity by up to 16% than the proposed method that considers different modal contributions for all effective modes.

Table 4. Comparison of SFA Results

	Single Mode Case		Multimode Case		HCLPF Ratio b)
	A_m (g) a)	HCLPF (g)	A_m (g) a)	HCLPF (g)	
Containment Bldg.	4.93	1.22	4.73	1.29	0.94
Aux. Bldg.	2.03	0.54	2.16	0.64	0.84
CCWB	2.37	0.81	2.33	0.82	0.98
RWST	2.68	0.90	2.58	0.90	1.0
ESWB	0.63	0.26	0.62	0.26	1.0

Notes. a) median acceleration capacity (0.2g of reference earthquake level)
b) HCLPF of single mode case / HCLPF of multimode case

CONCLUSIONS

This paper introduced an improved response spectrum shape factor considering the multimode effects and discussed on its impact on the SFA results of shearwall structures. From the case studies of several typical NPP structures in Korea, the effectiveness and applicability of the new response spectrum shape factor have been validated. When the effect of different modal properties of each mode is not negligible, the response spectrum shape factor considering multimode effects should be adopted in SFA. Replacing the existing response spectrum shape factor by the newly improved factor, more reasonable seismic capacity of structure can be estimated. Its applicability would be more highlighted for irregular complex structures which have many effective higher modes.

ACKNOWLEDGEMENT

This study was partially supported by the Korea Electric Power Research Institute (KEPRI) and University of Incheon. The authors wish to express the appreciation for their financial supports.

REFERENCES

1. USNRC, PRA Procedures Guide - A Guide to the Performance of Probabilistic Risk Assessments for Nuclear Power Plants, Final Report, Vol. I & Vol. II, NUREG/CR-2300, US Nuclear Regulatory Commission, 1982.
2. Kennedy, R. P., et. al., "Probabilistic Seismic Safety Study of an Existing Nuclear Power Plant", J. of Nuclear Engineering and Design, Vol. 59, 1980, pp. 315-338.
3. Kennedy R. P. and Ravindra, M. K., "Seismic Fragilities for Nuclear Power Plant Risk Studies", J. of Nuclear Engineering and Design, Vol. 79, No. 1, 1984, pp. 47-68.
4. Ebisawa, K. C., et. al., "Evaluation of Response Factors for Seismic Probabilistic Safety Assessment of Nuclear Power Plants", J. of Nuclear Engineering and Design, Vol. 147, 1994, pp. 197-210.
5. Reed, J. W. and Kennedy, R. P., Methodology for Developing Seismic Fragilities, EPRI TR-103959, Electric Power Research Institute, Palo Alto, California, 1994.
6. Ravindra, M. K., "Seismic Individual Plant Examination of External Events of US Nuclear Power Plants: Insights and Implications", J. of Nuclear Engineering and Design, Vol. 175, 1997, pp.227-236.
7. Park, B. Y., et al., "Probabilistic Seismic Fragility Analysis for Nuclear Power Plants (in Korean)", Proc. of KSCE Conference (I), Korean Society of Civil Engineers, 1992, pp. 125-128.
8. Joe, Y. H. and Cho, S. G., "Seismic Fragility Analysis of Multi-Modes Structures Considering Modal Contribution Factor (in Korean)", J. of the Earthquake Engineering Society of Korea, Vol. 6, No. 4, 2002, pp. 15-22.
9. Joe, Y. H. and Cho, S.G., "Effects of the Recorded Earthquake Data on the Seismic Fragilities of Korean Nuclear Power Plant Structures", J. of the Computational Structural Engineering Institute of Korea, Vol. 16, No. 3, 2003. 9, pp.321-331.
10. KEPCO, Individual Plant Examination of External Events For Yonggwang Nuclear Units 3&4(YGN3&4), Final Report, Korea Electric Power Corporation, 1993.
11. USNRC, Design Response Spectra for Nuclear Power Plants, Regulatory Guide 1.60, Rev. 1, U.S. Nuclear Regulatory Commission, 1973.
12. Newmark, N. M. and Hall, W. J., Development of Criteria for Seismic Review of Selected Nuclear Power Plants, USNRC Report NUREG/CR-0098, US Nuclear Regulatory Commission, 1978.